Boom Dynamics during Control System Response on Agricultural Sprayers

by

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Abstract

Farm managers use highly productive and mechanized agricultural sprayers to efficiently cover cropland. These sprayers use modern control systems including automatic section control (ASC) capabilities to manage target application rates. These “precision” technologies typically provide many benefits to users but also have limitations. Therefore, this study was conducted to evaluate spray boom dynamics during rate control system response on agricultural sprayers. A methodology was established to evaluate boom flow dynamics for agricultural sprayers using rate control systems equipped with ASC technology. Field tests with a John Deere 4930 (36.6 m spray width) having auto-boom capabilities and an AG-Chem Rogator SS 1074 (30.4 m) with auto-nozzle control were conducted to assess nozzle uniformity and accuracy during field operation. Additionally, a Schaben 18.3 m sprayer was selected for conducting static tests. Individual boom- and nozzle-section(s) were turned OFF and then back ON when using flow and no-compensation. Tests were also conducted by simulating a sprayer moving OUT and then back INTO point rows at different angles. Further, two different flow control configurations were evaluated involving 2-way and metered 3-way boom shut-off valves to study the impact of control hardware on nozzle flow performance during ASC actuation. Finally, the impact of control components response tuning on nozzle flow stabilization was studied using different flow regulating valves.

Nozzle off-rate was beyond ± 10% of the target rate for both rectangular and irregular fields. Nozzle off-rate occurred for a greater percentage (65%) of time in irregular shape fields primarily due to frequent ground speed changes and ASC actuation. Overall, the control system response resulted in greater under-application (49%) than over-application (17%) during field tests. Static tests involving ASC actuation and ground speed variations supported field results. Nozzle pressure and corresponding flow deviated between 4 and 18% from target rates when boom-section(s) were turned OFF and back ON. Nozzle flow was always higher (4 to 18%) and exhibited long settling times (up to 25 s) as compared to the overall system flow. The difference in pressure increase was statistically different between auto-boom and auto-nozzle control and also for compensation and no-compensation. Control system response resulted in over-application (up to 11%) when moving OUT and under-application (up to -37%) when moving back INTO point rows. Nozzle flow was beyond ±5% the target rate (off-rate) for up to 19 s. The control system was able to maintain flow compensation during 70° point row operation but uncontrolled transient responses on 20° point row angle. Flow control configuration impacted nozzle flow settling time and off-rate times for different point row angles, ground speeds and application rates. No transient response during ASC actuation was observed for metered 3-way boom shut-off valves whereas the 2-way boom valves exhibited under-damped (exiting point row) and over-damped (reentering point row) response. The nozzle flow settled quicker with metered 3-way boom valves (within 4 s) as compared to the 2-way valve (1 to 28 s) configuration, thereby impacting off-rate times. The regulating valve calibration number also impacted nozzle flow settling times (response). Overall, the total off-rate times for both the 2-way and metered 3-way boom shut-off valve setups increased as ground decreased and point row angle increased. Thus, flow control configuration, control hardware feedback and response, and control algorithms are critical for expected management of crop inputs. In conclusions, the control hardware and algorithms used within controllers must be designed and tuned to minimize off-rate errors. These modifications are specifically critical as the control resolution decreases down to individual nozzle control on future agricultural sprayers.

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CHAPTER 1
INTRODUCTION

1.1 BACKGROUND

Advances in farm mechanization have contributed to growth in agricultural production during the 20th century. The current global population of seven billion is projected to increase another 40% (U.N., 2011) by 2050 thereby increasing the demand for food, fiber, feed and energy. Refinements in agricultural production techniques are helping producers to continuously improve management of soil, water, nutrient, and pests to increase the yield potential of crops. Pests can cause losses both in terms of overall yield and quality. Among different farm operations, producers undertake a number of pre- and post-emergence spray applications for pest management. The accumulation and maturity of pests can also negatively impact yields in the subsequent seasons. Therefore, pest management is a key ingredient to effective and economic production of crops on a sustainable basis (Al-Gaadi and Ayers, 1999).

Application of crop inputs such as chemicals should have a minimal impact on natural resources such as soil and water for sustainable agricultural production today and in the future (WCED, 1987). Therefore, agricultural sprayers used for pesticide and nutrient applications are needed to accurately apply on target areas at the rates prescribed on product labels. Application rates beyond the target can result in over-application. Further, off-target application can impact environmentally sensitive areas (Figure 1.1) such as grassed waterways and buffer strips. Over-application results in direct product loss which can be carried with run-off from agricultural fields. Runoff containing pesticides from agricultural fields causes non-point source pollution whereas nutrients such as nitrogen and phosphorus can cause eutrophication thereby negatively affecting water bodies by creating dead zones or hypoxia (CENR, 2010). On the contrary, under-application does not effectively manage pests and can cause chemical resistance among pests. Chemical resistance due to under-application may require producers to alter or undertake additional management practices which could increase production costs. Additionally, fixed orifice nozzles are commonly used during spray applications. Spray application beyond the target rates can impact nozzle pressure, droplet size, and spray distribution. Therefore, a conscious selection of the appropriate spray technology has to be made for efficient pest management.

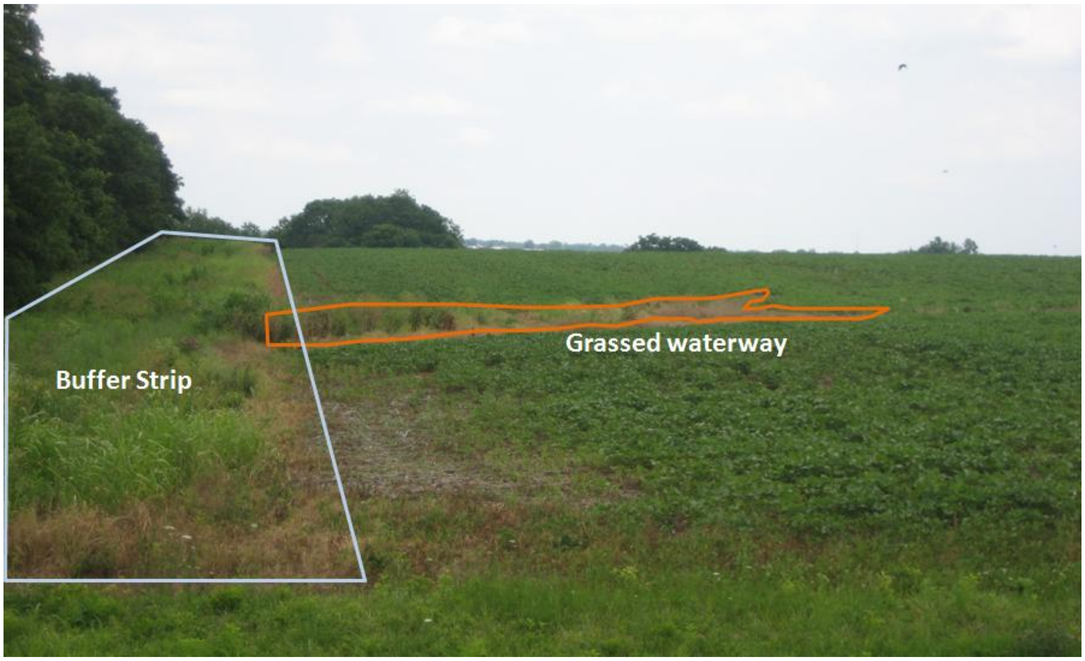


Figure 1.1. Example of a chemically impacted grassed waterway and buffer strip.

In the past, a basic agricultural spray control system consisted of a pump, pressure relief valve, and manual control valve. While other components may be used, these were the primary means for controlling the application rate. The premise was for the operator to manually set the system pressure with the control valve based on the desired target rate and expected operating ground speed. Once set, the system pressure was not changed while the operator attempted to maintain a constant ground speed during application. Typical boom widths and ground speeds of these sprayers were 9 m and 9.7 km h^{-1}, respectively (Ayers et al., 1990). Any deviation from the desired ground speed would result in application errors (i.e. over or under application) since system pressure does not automatically adjust. Operators make frequent turns at headlands and traverse other obstacles in the field making it difficult to maintain a constant ground speed. Consequently, the overall accuracy of pressure-based application systems mainly depend on the operator's ability to properly calibrate then maintain the desired ground speed.

Over the years, the U.S. workforce employed in agriculture has decreased to 1.4% (USDA, ERS 2000) with more than 65% of the total farm land having operations size of 1,000 acres or more (USDA, ERS, 2002). Sprayer operators have a challenging task to efficiently cover sufficient area per day to timely apply inputs while keeping farming economically viable in current global markets. To keep pace with producers' requirements and to increase field capacity of sprayers, swath widths have become larger and operating speeds have increased. Presently, self-propelled sprayers are the most common in the U.S. (Figure 1.2) with nominal widths of 27.4 and 36.6 m being popular. The booms for these sprayers are typically divided into 5, 7 or 9 boom-sections, which can be turned OFF or ON independently allowing the operator to spray at different widths. These large sprayers are equipped with electronic rate control systems that regulate the overall system flow. These control systems use a ground speed sensor; a flow meter for feedback to the controller; and a flow regulating valve, boom shut-off valves and a micro-processor based controller to handle the control aspect of spraying. The control system automatically regulates product metering to maintain the target application rate. Therefore, the rate controller has the ability to adjust the regulating valve until the system flow rate matches the target rate regardless of the ground speed or width of spray. Unlike simple pressure-based sprayers, the operator does not have the responsibility of maintaining a constant ground speed since flow is adjusted automatically.

Figure 1.2. An example of a commercially available 27.4 m wide, self-propelled agricultural sprayer.

To further improve sprayer productivity and efficiency, current control system hardware and software have the capabilities to integrate a global positioning system (GPS) receiver to provide accurate ground speed, machine guidance, and other control or mapping aspects. Machine guidance reduces gaps and overlaps thereby decreasing operators' driving error by maintaining consistent parallel, adjacent passes. Producers can also use these systems to spatially monitor and manage parts of the fields with similar soil and plant growth potentials with greater ease and improved productivity. In this case, producers can implement variable-rate application (VRA) of crop inputs in which rates are varied when traversing a field. However, even with these control systems, the operator has to manually turn individual boom-sections OFF or ON by differentiating between sprayed areas and areas still to spray. While turning boom-sections ON and OFF may be easily performed in rectangular fields, it becomes more complex in non-rectangular fields, with the presence of grassed waterways and field obstacles, and curvilinear machine travel within field boundaries. Therefore, these field conditions require a control system with enhanced automatic machine parameter control and higher application resolution to reduce unwanted spray application errors due to operator response.

Recently, modern rate control systems have incorporated automatic section control (ASC) technology for use on agricultural sprayers. ASC technology is capable of independently and automatically controlling the ON and OFF of boom- or nozzle-sections. This technology uses a GPS receiver to automatically turn boom- or nozzle sections OFF in areas which have been previously sprayed such as headlands or in environmentally sensitive areas requiring no-spray (e.g. grass waterways, buffer strips, etc.) as shown in Figure 1.3. ASC turn on these sections independently. Operators using ASC can decrease product over-application and reduce applied areas (Luck et al., 2010a). One study has suggested that producers can decrease over-application by 12.4% (Luck et al., 2010b) depending upon the number of control sections and no-spray areas in the field. These benefits directly translate into reduced chemical usage and thereby reduced environment risks. Pesticide costs in the U.S. have steadily increased from $140 million in 1949 to $11.5 billion in 2009 (USDA, 2010) (Figure 1.4). Therefore, even with a modest 8% reduction in chemical usage, ASC would result in roughly $921 million in savings for the U.S. and more specifically $9 million for the State of Alabama. These flow control systems in conjunction with crop sensing technologies such as GreenSeeker™, Crop Circle™ and CropSpec are also being used to sense and apply nitrogen based on crop status or stress. Research using crop sensors have revealed that producers can achieve high nitrogen use efficiency by using optical sensor-based nitrogen management (Singh et al., 2011).

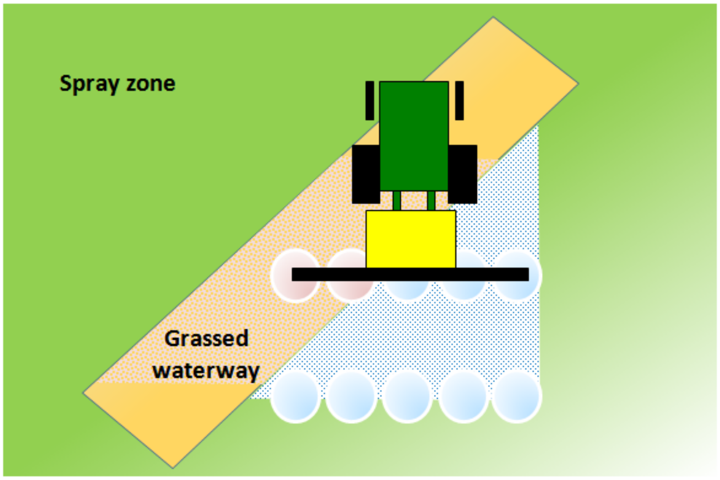


Figure 1.3. Controller automatically switches boom-section(s) (indicated as circles) off (represented in red circles) on grassed water-ways while keep sections on (represented by blue circles) for spray zone.

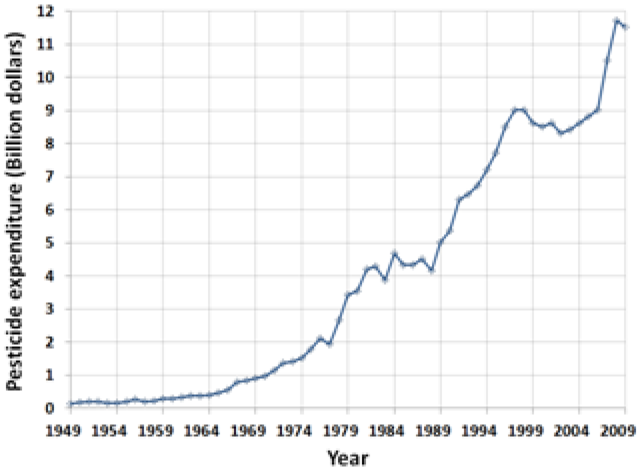


Figure 1.4. Pesticide expenditure on U. S. farms from 1949 to 2009 (UDSA, ERS, 2010).

Rate control technologies have improved operators' productivity, but the cost of installing modern technologies can be substantial. Rate control systems currently cost from $5,000 to $48,000 depending on its capabilities and components such as control hardware, GPS receiver and correction service, guidance system, and boom height control to name a few. Additionally, past research on control systems has highlighted that application rate errors can occur during field operations for agricultural sprayers. These errors have been attributed to improper calibration, nozzle wear, operator error, and control system response time delays (Grisso et al., 1989; Hofman and Solseng, 2004; Anglund and Ayers, 2003).

Application errors could magnify when using existing flow control systems including ASC technology on the larger sprayers used today. Understanding the actual performance of these technologies is required for adoption by producers and also allow technology and agriculture manufacturers to design sprayers to meet expected performance.

1.2 MOTIVATION

Spray application is a dynamic operation which requires sophisticated control systems that are complex for both industry and users to understand. Modern control systems are using new technologies to reduce operators' responsibility during spray applications. This rapid evolution of spray control technology is outpacing the basic understanding of the actual performance and limitations. Often operators trust the functionality of spray control technology by assuming it works as advertised. However, the entire control system has to work precisely and respond in a timely fashion. During field operation, control system response to dynamic flow rate change can influence overall performance accuracy of the system. Therefore, system accuracy depends upon the resolution and response of individual components in the feedback and control network. The response of components such as the flow meter, flow regulating valve, boom shut-off valves, GPS receiver, and controller processing capacity dictates response of the control system. The processing capacity and response time can be critical especially as control becomes more complex and demanding to achieve greater resolution and accuracy. Although control systems are being continuously redesigned to improve performance, these systems may continue to have practical response delays. Thus, these spray control technologies need to be evaluated and well understood to ensure proper operation and performance. These results will help producers differentiate between perceived and actual benefits of the technology. Operators can bring value to their operation by understanding machine management factors impacting field performance of sprayers. Therefore, evaluation of spray control system performance will highlight real benefits of these technologies, increase management of crop inputs, enhance operator productivity, increase user confidence, and augment the goal of environmental stewardship.

1.3 HYPOTHESIS

Based on the above review and current knowledge on sprayers, the following hypotheses were formulated for this research:

1. Commercial rate controllers with automatic section control capabilities can provide application accuracy during typical field operations.
2. Nozzle pressure across a sprayer boom remains stable for system flow transitions when controlling boom-section(s) or combination of individual nozzle-level actuations.
3. Rate controllers with automatic section control (ASC) technology can regulate real-time spray dynamics during distinctive field operating situations, such as transitioning between spray and no-spray zones at acute angles.
4. Flow control hardware and tuning has an impact on sprayer performance.

1.4 RESEARCH OBJECTIVES

During field operation there are rapid changes in the boom dynamics and inconsistency in the flow rate and/or pressure due to response lag times. Further, a sprayer operator has difficulty in identifying rate control response and potential application errors from the cab. In return, the operator is unable to adjust machine and technology setup to minimize errors. Therefore, the overall goal of this research is to evaluate control systems and nozzle response when implementing ASC on agricultural sprayers. The objectives of this research are to:

1. Compare the performance of different commercially available spray control technologies under field operation,
2. Quantify nozzle pressure variations across a sprayer boom for different system flow state transitions during boom-section(s) and individual nozzle-level ON and OFF conditions,
3. Determine nozzle flow dynamics when varying location of ON and OFF control within the boom plumbing plus actuation timing, and
4. Evaluate the impact of different flow regulating valves and their response tuning on nozzle flow stability when actuating automatic section control technology.

1.5 DISSERTATION OUTLINE

This dissertation is presented in manuscript format for those chapters discussing the methodology and results. Chapter 1 provides an introductory overview justifying this research while presenting the research objectives. Chapter 2 covers a review of literature and information related to agricultural sprayers and spray control technology. Chapters 3 through 6 present in manuscript format a discussion and response to the four objectives outlined for this research. Chapter 3 compares nozzle accuracy and uniformity using different commercial spray technologies during field and static tests. Chapter 4 documents the preliminary tests quantifying pressure variations across a boom during auto-boom and auto-nozzle actuation. Chapter 5 demonstrates off-rate errors during point row operation when using ASC technology. Chapter 6 covers the effect of flow control hardware on nozzle flow response when using ASC technology. Finally, Chapter 7 summarizes this research project by presenting the overall conclusions, future research suggestions and practical implications of the research findings. References and appendices are included citing major hardware components, instrumentation and software specifications for all equipment utilized as well as example LabVIEW code screen shots.

CHAPTER 2
LITERATURE REVIEW

Spray application is an important aspect of effective and economic management for producing crops on a sustainable basis. Crop yield and quality depends greatly on the correct amount of applied pesticide across the field (Ozkan, 1987). Adverse effects of no chemical application can include up to a 20% decrease in crop yields along with negative effects of pest accumulation in subsequent seasons (Hawkins et al., 1977). Crops can require routine pesticide and nutrient applications, but the high degree of inaccuracies associated with chemical application during field operations can impact the environment and generate unwarranted cost of inputs. Furthermore, the timing of spray applications is critical for most pesticide applications to ensure products are effective in their intended treatment.

2.1 AGRICULTURAL SPRAYERS

A basic agricultural spray system consists of a tank, pump, hoses and plumbing, manual control valve, pressure relief valve, and manual boom shut-off valve (Figure 2.1). These spray systems are designed to apply liquid formulations uniformly over an area of interest. Nozzles are selected based on the target application rate and expected ground speed. The target pressure related to the target nozzle flow is set using the manual control valve. The spray system is then calibrated to apply the predetermined tank volume uniformly over the field. Calibration is also conducted to ensure that accurate ground speed is provided to the operator so as the actual nozzle flow (L min^{-1}) at the expected system pressure, matches the target flow. Similarly during nozzle calibration, if the volume collected from any of the nozzles deviates more than 10% compared to a new nozzle output, those nozzles are replaced. Once calibrated, the operator prepares a tank mix of chemical in quantities as a function of size of the field, predetermined application rate, and the chemical label. Finally, the operator applies chemical keeping the ground speed as constant as possible to achieve uniform application. Therefore, the actual application rate matches the target rate only in those areas where vehicle speed is maintained at the desired speed. The overall accuracy of application depends highly on proper calibration plus the operators' driving skill and response during field operation.

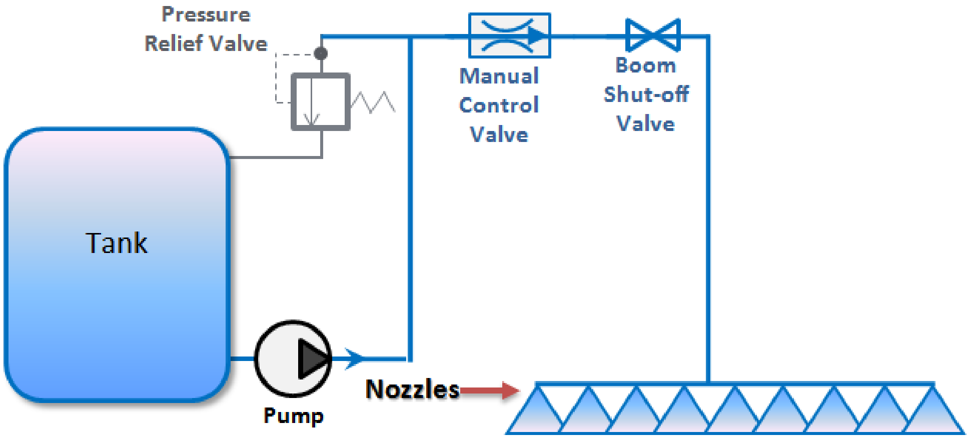


Figure 2.1. Basic agricultural spray system.

2.1.1 BASIC COMPONENTS OF AGRICULTURAL SPRAYERS

To overcome application errors due to inevitable ground speed variations and other operator errors, electronic spray control systems were developed and mostly used now to manage the target application rate during ground speed variations. A typical spray control system or rate controller consists of a ground speed sensor, flow meter, regulating control valve, boom valves and microprocessor based controller (Figure 2.2). The control system commonly uses ground speed radar or now a global positioning system (GPS) receiver to provide speed measurements. The system utilizes an inline flow meter to measure system flow rate providing feedback to the rate controller which in return adjusts the regulating valve to achieve the target system flow. The target system flow is a function of ground speed, width of spray, and application rate (L ha^{-1}) set in the controller by the operator. Further, a control system uses feedback from the system flow meter and sends control commands to the regulating valve to adjust system flow with the calculated value.

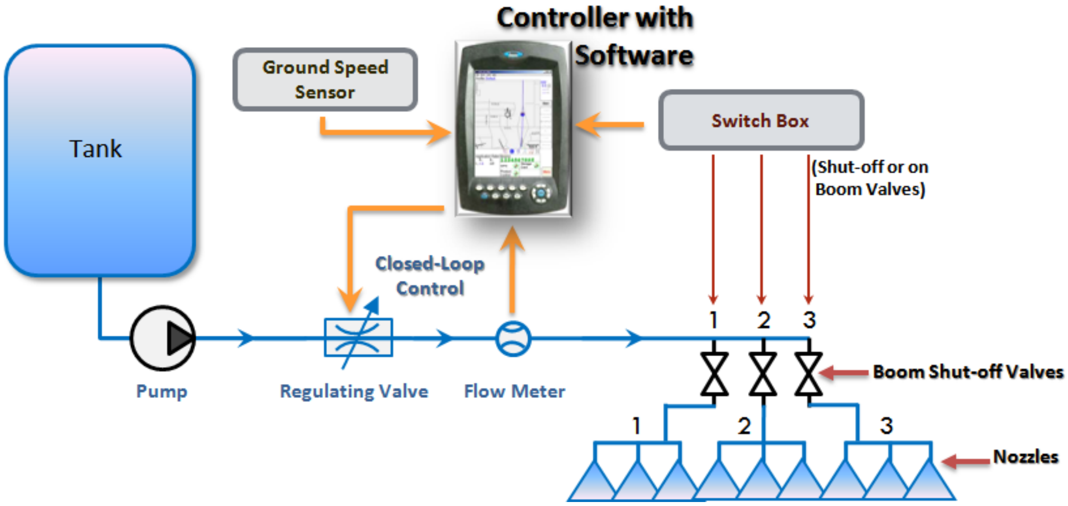


Figure 2.2. A typical microprocessor based rate control system.

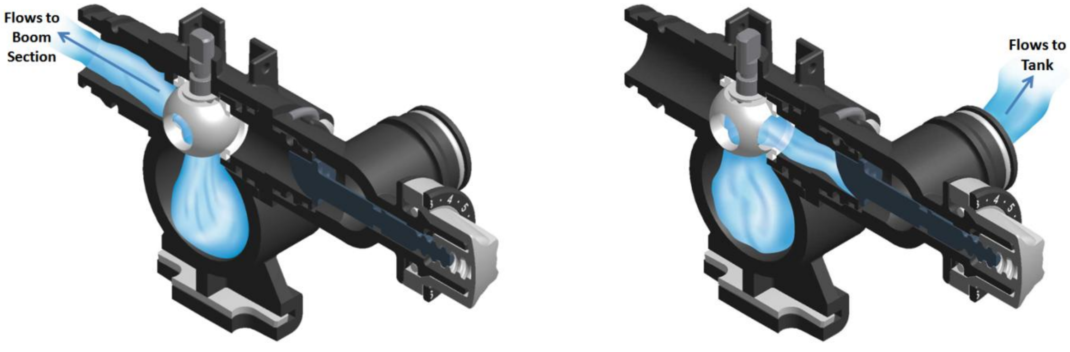
The flow of product to the boom is shut ON and OFF using a boom shut-off valve (Figure 2.2). These valves allow the operator to shut the sprayer ON and OFF when turning around on ends (e.g. headlands) or areas previously sprayed or do not require product. Most agricultural sprayers have booms split into what are termed “boom-sections” allowing for independent ON/OFF of these sections across the boom. This setup permits the operator to manually turn a portion of the boom OFF versus the entire boom using a switch box (Figure 2.2) located in the operators station. Partial boom width can be required at times during field operation. Therefore, turning sections OFF can reduce over-application of product. In the U.S., 2-way boom shut-off valves are popular on agricultural sprayers.

The 2-way boom valve is simply an ON/OFF boom valve which either allows product flow (on-state) or no-flow (off-state) to the boom-section. When the 2-way boom valve is shut-off, the product volume intended for that boom-section temporarily remains in the system as the control system regulates flow to the new target value. A sprayer setup with 2-way boom shut-off valves uses flow feedback and regulating valve to adjust system flow to represent the number of boom valves ON; the new spray width. This system flow regulation during ON and OFF action of boom shut-off valves, conserves target application rate (L ha^{-1}) and is termed as flow compensation. However, if the flow controller is not present, the system flow is not regulated during boom shut-off valve actuation and is termed as no-compensation. Alternatively, a 3-way boom valve can be used to shut product flow ON and OFF (Figure 2.3). However, a 3-way boom valve has one inlet and two outlets in comparison to one inlet and one outlet for 2-way valve. The one outlet of an 3-way valve is connected to the boom-section while the second outlet is attached to a return line to the tank. Although, the 3-way boom valve performs a similar function of shutting the flow ON or OFF to the boom-section, it manages the flow differently during shut-off (Figure 2.3). During boom valve shut-off, the flow of that section is redirected back to tank through the return line. Thus, the 3-way boom shut-off valve can maintain set system pressure or corresponding flow irrespective of the valve being in the OFF or ON state. However, 3-way boom valves also required a controller, flow meter feedback and regulating components to maintain the target rate during ground speed changes.

2.1.2 RATE CONTROL SYSTEMS

Rate control systems regulate system flow rate thereby they are termed as “flow based” control systems, whereas some of the control systems are termed as “pressure based” as they control system or nozzle pressure. However, flow based systems are commonly used since it is easier to manage system flow versus pressure. However, proper tuning and setup of the speed sensor, flow meter, regulating valve and boom valves within the control system is essential to accurately regulate system flow within expected response times.

To setup a flow based system, the operator programs the flow meter and regulating valve calibration numbers (VCN) in the controller as instructed by the manufacturer. Once the controller is programmed the operator rarely alters the recommended VCNs. The flow meter calibration number accurately establishes system flow rate whereas the regulating valve VCN defines the expected response of the control valve motor during system flow rate management. The 1st through 4th digit of regulating valve VCN represents valve backlash, speed, break point, and dead band digits. The first digit represents the valve backlash digit, which controls the time of the first correction pulse after detecting a change in correction direction of the valve and have a range from 1 (short pulse) to 9 (long pulse). The second digit controls the response time of the control valve motor with a range of 0 (fast response) to 9 (slow response). The third digit is the valve brake point digit, or the point at which the control valve starts to turn at a slower rate to avoid overshoot when adjusting to the target rate. The values of the break point range from 0 to 9, where 0 corresponds to 5%, 1 to 10% and so on up to 9 for 90% of the target rate. The fourth digit represents the dead band and sets the permissible difference between the target rate and the actual application rate.



(a) (b)

Figure 2.3. Illustration of flow through a metered 3-way boom valve in the open (a) and closed (b) position (Teejet Catalog 51, 2011).

An alternative approach towards spatially controlling the application rate is to adjust the applied dosage by varying the volume of injected chemical to maintain application rate (Ayers et al., 1990). These systems are termed direct injection control systems as the chemical is directly injecting chemical into the outgoing water flow. The direct injection system has a separate tank(s) for chemical(s), metering system for precise chemical injection and feedback mechanism to maintain target chemical injection rate. The system maintains the target injection rate by regulating the speed of the chemical injection pump based on ground speed, target application rate, and width of sprayer. The flow rate of carrier (water) is usually kept constant. Since the flow of chemical injected is significantly less when compared to the carrier, the direct injection system produces little variation in nozzle pressure when adjusting the chemical rate. Additionally, since an injection control system does not require a premix of chemical, the leftover chemical in the injection tank can be saved for future application. The principal limitation of this system is the transport delay incurred between the point of chemical injection and nozzle discharge. This transport delay refers to the time that system takes to establish the new target or adjusted chemical rate at the nozzle. This transport delay time can result in the sprayer traveling certain distance resulting in application rate errors (Rockwell and Ayers, 1996).

2.1.3 AVAILABLE SPRAYERS AND ASSOCIATED PRODUCTS

Boom widths for sprayers have continued to increase in the US. Agricultural sprayers from John Deere, AGCO, Case New Holland (CNH), Hagie and others manufacturers have nominal boom widths of 18.2, 27.4 and 36.6 m. Although boom widths for agricultural sprayers can be smaller or bigger, the 27.4 m and 36.6 m widths are common in the U.S. The sprayer booms are typically designed for 5, 7 or 9 boom-sections, though individual nozzle control can also be attained using recent technology. The increased application widths coupled with varying field shapes and sizes, commonly found in the southeastern US, can be demanding on rate control systems to have quick response in order to maintain application rates while minimizing off-rate errors. Current rate control packages can include sub-inch GPS receivers, ASC technology, auto-boom height control, vehicle guidance, touch screen consoles, remote data transfer from the controller to a producer’s computer and using wireless technology. With all these technologies on board, an operator can now cover more acres and save product regardless of terrain, shape and size of the field.

2.2 TEST PROTOCOLS RELATED TO AGRICULTURAL SPRAYERS

According to available test standards, the coefficient of variation (CV) is used to measure lateral spray distribution uniformity across the spray boom, as outlined in the International Organization for Standards (ISO) 5682-3 (ISO, 1997)-Test method for volume per hectare adjustment systems of agricultural hydraulic pressure sprayers and American Society of Agricultural and Biological Engineers (ASABE) standard S386.2 (ASABE, 2009) calibration and distribution pattern testing of agricultural aerial application equipment. According to these standards, nozzle uniformity (CV) is calculated using the equation:

$$\mathrm{CV} = \frac{s}{\overline{x}} * 100$$

Where s = standard deviation (L min^{-1})

$\overline{x}$ = mean volume rate (L min^{-1})

ISO 5682-3 (ISO, 1997) also outlines test methods for volume per hectare adjustment systems to measure deviation of actual nozzle flow from the target (nozzle rate error). This standard is applicable to systems that allow application of a pre-determined constant volume of chemical spray mixture per hectare independent of variation in driving speed.

Draft International Standard ISO/DIS 16122-2 (ISO, 2011) for horizontal boom and similar sprayers, states that nozzle uniformity (CV) across the boom should not exceed 10%, although the sprayer industry tends to accept a limit of 7% (Teejet, 2011). If uniformity exceeds 7%, then it is recommended to replace worn tips or install new ones (Figure 2.4). The nozzle wear can be measure using an ASABE Standard S471 (ASABE, 2008), procedure for measuring sprayer nozzle wear rate. Draft International Standard ISO/DIS 16122-2 (ISO, 2011) also includes requirements and methods of verification for testing nozzle off-rate with flow measuring, control and regulation systems plus provides methods to test nozzle rate errors by turning boom-sections ON one by one. The off-rate can be measured using nozzle flow measurements or installing a standard calibrated flow meter on the circuit of the sprayer. These tests measure the error between the expected and actual system flow rate or nozzle flow. The actual nozzle flow is measured by multiplying the mean single nozzle flow (at the operating pressure) with the number of nozzles which are ON. During these tests, the pressure variation measured at the inlet of the boom-sections, should not be more than 10%. According to the Guide for Commercial Applicators (USEPA and USDA, 1975) and Rietz et al. (1997) the actual application rate should be within 5% of the recommended label or target rate. However, the typical accepted off-rate error commonly used within the sprayer industry is ±10%. The larger accepted error by the sprayer industry might suggest the difficulty in controlling target rates consistently within 5% especially during field operation. Overall, the sprayer can be set and calibrated using the ASABE standard S592 (ASABE, 2007), best management practices for boom spraying and ASABE Standard EP367.2 (ASABE, 2008) guide for preparing field sprayer calibration procedures.

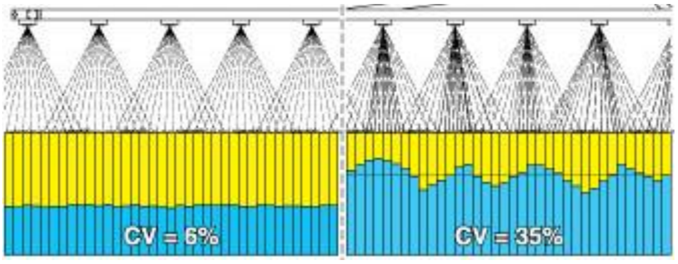


Figure 2.4. Illustration of nozzle flow with acceptable and unacceptable uniformity (Teejet, 2011).

Although these methods outline nozzle uniformity and nozzle rate error tests when turning boom-sections ON one by one, they do not present any guideline to measure these parameters during dynamic, boom-section control (e.g. ASC technology). During typical field operations boom-sections turning ON and OFF along with ground speed variations can occur simultaneously. Therefore, considerations for these common operating conditions with sprayers are also needed to understand and evaluate nozzle uniformity along with rate errors.

2.3 APPLICATION ACCURACY AND EFFICACY

Several studies have been performed to assess the performance of agricultural sprayers during field operation. Past evaluations conducted on private and commercial pesticide applicators indicated that only 40% of the applicators were within 10% of the intended application rates (Rider and Dickey, 1982; Nelson, 1986). Grisso et al. (1989) conducted a field survey of 103 private applicators in 12 central and eastern counties of Nebraska and reported that only 30% were applying herbicide within 5% of the intended target, 44% under-applied and 26% over-applied herbicides. The cost of over-application amounted to $3.11/ha and at this rate with the loss estimated at $4.26 million for the state of Nebraska. Gerling (1985) reported that out of 150 sprayers inspected by the DuPont Company on farms in North America, about 60% applied less than the target application rate with only 33% applying within 10% of the target. Sprayer application errors were reported to be typically due to worn nozzles, inaccurate calibration, or inability to maintain the required flow rate during field application (Grisso et al. 1989; Hofman and Solseng, 2004).

Sprayer operators using pressure-based systems rely on ground speed feedback to match the target application rate. Therefore, during spray application if the operator deviates from the target ground speed, the actual application rates can be greater (speed less than target) or less (speed greater than target) than the target rate. It was reported that more than 25% of liquid pesticide applicators during field work operated beyond ±10% of the target ground speed established for the sprayer and its setup (Grisso et al., 1988; Hofman and Hauck, 1983), resulting in application rate errors. Most importantly, mechanical speedometers (relating transmission speed directly to ground speed) did not take into account wheel slip allowing the operator to unintentionally deviate from the target application rate. Sprayer operators can also impact the application performance by deviating from the desired path, leaving behind skipped areas or spraying the same area twice or even three times. It can be difficult for the operator to precisely keep track of areas which have been sprayed (e.g. headlands), areas that still require application and those which do not need spraying. Agricultural fields can also include grassed waterways placed on highly erodible areas or vegetative filter strips to reduce transport of pesticides or nutrients into streams or other environmentally sensitive area via runoff. However, in reality operators use field rows or other field structures to make a rough estimate of sprayer current location when manually switching the spray boom ON or OFF. Additionally, these structures are hard to distinguish thereby operators are not able to accurately shut-off booms. The operator's lag in timely shutting boom-sections OFF or ON can lead to application errors.

2.2 PERFORMANCE OF RATE CONTROLLERS

Rate control systems can use a variety of components for feedback and adjusting system flow. Components may vary with application requirements but the overall sprayer application accuracy depends on the performance of the rate control system.

2.2.1 CONTROL SYSTEM ACCURACY

Ground speed radar sensors were found to be accurate for ground speed measurements (Tompkin et al., 1988; Khalilian et al., 1989) in past studies. These speed sensors use ultrasonic waves with speed estimated based on Doppler effect. These ground speed sensors reduced speed measurement errors versus fifth wheel and front wheel, thereby aiding control systems to accurately establish target system flow rates. It should be noted that these studies were conducted prior to GPS receivers becoming the primary input for ground speed. Ayers et al. (1990) investigated the performance of a Dickey-john SC1000 pressure-based, sprayer control system and reported that it was able to maintain an error of less than 5% when ground speeds varied from 3.2 to 9.7 km/h. More specifically, this pressure control system provided application rates ranging from 282 to 298 L/ha (30.1 to 31.9 gpa), which resulted in an error ranging from -1.1 to +4.6%. In another study, Al-Gaadi and Ayers (1994) studied the performance of a ground driven boom sprayer when operated with and without a Dickey-john CCS 100 pressure-based, sprayer control system. The sprayer was equipped with a data acquisition system, flow meter and ground speed radar. They concluded that the use of a spray controller reduced the application errors from between -18% and 5% down to -7% and 1%. Thus, sprayers for applying chemicals at constant and variable rates with both pressure based and injection sprayer technology were able to provide accurate application rates within 2.25% of the target rate (Anglund and Ayers, 2003).

The dynamic response of pressure-based control systems during a step change in application rate or ground speed was another important factor defining the accuracy of these systems. Rockwell and Ayers (1996) designed and constructed a variable-rate, direct nozzle injection field sprayer. They concluded that the mean time constant was 2.5 s with an average rise time of 3.8 s. The time constant of the system represented the time required to reach 62.3% of the step input while the rise time equaled the time needed to transition from 10% to 90% of the step input. The reaction time included both transport lag and total response time.

Tompkins et al. (1990) measured chemical concentration at the nozzles to ascertain uniformity of chemical concentration by changing the injection location between immediately upstream of the pump, immediately downstream of the pump and at the individual nozzle. They concluded that in all three cases, as the injection point was moved downstream in the system, the transient time required to produce uniform chemical concentration in the nozzle effluent was reduced. On the contrary, the degree of mixing (chemical and carrier) decreased as the injection point was moved downstream of the system pump resulting in variation in chemical concentration both among nozzles and over time. Computer simulations were conducted by Way et al. (1992) to assess chemical injection application accuracy on sprayers while accelerating at 1.6 km h^{-1} s^{-1} from rest to a constant speed. The comparisons were made among injection sprayers and conventional tank-mix sprayers without sprayer controllers.

The results highlighted that the ratio of area receiving unacceptable chemical application rates to the total area sprayed was smaller for the tank-mix sprayer than for any injection based sprayer.

Dynamic and steady state performance of a commercial chemical injection system, by changing system pressure and simulated sprayer travel speed, was also studied by Sudduth et al. (1995). They reported that little variation existed in nozzle output distribution (CV < 10.5%) and chemical concentration (CV < 7.0%) across the spray boom. Further, the delays in the injection controller and injection pump was approximately 1 s and 4 s, respectively.

Research has also been conducted to spray weed concentrated areas based on their spatial location. Giles and Slaughter (1997) developed a ground-based, precision applicator for foliar spray to rows of small plants. The system consisted of a machine vision guidance system that positioned spray nozzles directly above each row of small plants. The electrically actuated mechanical linkage rotated the flat fan nozzles to effectively change the width of the spray pattern relative to direction of travel and width of target plants. They concluded that the system reduced application rates by 66% to 80% and increased spray deposition efficiency on target plants by 2.5 to 3.7 times, as compared to conventional broadcast spray. Also non-target deposition on soil surfaces was reduced by 72% to 90%.

The accuracy of a control system depends on the accurate measurement of ground speed among other control components. Kees (2008) used a global positioning system (GPS) reciever, computerized controller and flow meter to manage system pressure by adjusting the speed of the pump to maintain a constant 187.1 L ha^{-1} application rate. The results demonstrated that as travel speed varied from 3.2 to 9.7 km h^{-1} a control system utilizing a GPS receiver for speed input maintained the actual application rate within 10% of the target rate. Transient errors in chemical application rate could also be impacted by the accuracy of the ground speed sensing mechanisms (Vidrine et al., 1975). Tompkins et al., (1998a) and Khallilian et al., (1989) evaluated different ground speeds and found that radar sensors worked well on firm soils but tended to provide erratic and inaccurate measurements in tall vegetation. The error in sensing the accurate ground speed can result in deviation from the target application rate thereby resulting application rate errors (nozzle off-rate).

2.2.2 FLOW CONTROL HARDWARE PERFORMANCE

The field performance of a spray applicator largely rests on accurate response of the spray control system when adjusting flow to maintain the target rate. Although the pressure and injection control system can help increase accuracy by automatically regulating system flow, the concerns existed regarding the lag time in managing nozzle rate, chemical mixing and uniformity of concentration at each nozzle. The lag time in pressure-based systems was the difference between the time when the input command for the change in nozzle pressure was sent to the control system and the time when the desired nozzle pressure was finally attained. For injection control systems the application errors have been associated largely with transport lag (Zhu et al., 1998; Tompkins et al., 1990; Miller and Smith, 1992). The transport lag for the injection control systems were the difference between the times when the change in chemical concentration was initiated to when it was finally achieved at the nozzle. Rockwell and Ayers (1996) stated that the transport lag is a function of the length of travel (length of hose) between the chemical injection point and the nozzle of interest but also solution velocity. They found that this delay in achieving the target rate at the nozzle could have occurred each time there was a change in ground speed or the desired rate (Rockwell and Ayers, 1996). Anglund and Ayers (2003) investigated the performance of ground sprayers for chemical application using both pressure and injection control systems. The transport lag in a pressure based system was found to be approximately 2.0 s due to GPS signal latency and control valve response lag, while the injection control system generated transport lag times from 15 to 55 s.

Additional research has also focused on the chemical concentration uniformities and flow characteristics along the boom. Miller and Smith (1992) evaluated errors associated with the performance of direct injection chemical applicators on a nozzle-by-nozzle basis. They found that the magnitude and temporal occurrence of error in the application rate was a function of lateral location of nozzles, while the error associated with tank-mix sprayers was a function of ground speed. Salyani (1999) studied the application rate error due to differences in pressure or flow rate by measuring nozzle pressure and flow on two air carrier orchard sprayers at six nozzle selections. He found that for all the nozzles, closure of the nozzles on one side of the sprayer increased the operating pressure and thereby flow rate on the other (open) side. Further, the pressure errors of the one-sided versus two-sided spraying was less than 20% for a centrifugal pump but exceeded 200% for a diaphragm pump system. They also concluded that volume rate errors at 470, 2350 and 4700 L ha^{-1} nominal rates were 1.0%, 3.5% and 3.5% (centrifugal) and 6.0%, 7.5% and 47% (diaphragm), respectively.

Rate control hardware response in achieving target application rate in a timely fashion is very critical as any hardware latencies if exist, can result in chemical misapplication. Qiu et al. (1998) developed a simulation model using SLAM II to assess the performance of a direct injection sprayer used for site-specific application of pre-emergence herbicide in corn. The study was conducted to study the effect of in-line mixing location, hose diameter, nozzle spacing and size, and ground speed on control system performance. Results of the simulation were input to GIS software to generate herbicide application rate maps and the corresponding error rate maps. They recognized that application errors for direct injection system were as high as 40% for mistreated areas of the field, with changes in chemical concentration at the remote nozzles occurring after as much as 80 m of travel past the point of a step change of the input command to the controller. They recommended moving the in-line mixing location close to the boom and using smaller line sizes to reduce line volume, without appreciably increasing pressure drop.

The use of GPS to determine sprayer spatial location extended the response time of the control systems during spray application. The reaction time was as high as 2.2 s for the control system in response to the differential global positioning system (DGPS) receiver (Al-Gaadi and Ayers, 1999). In another study on selective application of herbicide, it was reported that a resolution of 2.0 m was achievable for a DGPS receiver based control system and the minimum time delay for the system was 4.3 s (Stafford and Miller, 1993).

The flow control systems were also used to modulate the application rate using solenoid valves. The pulse width modulated (PWM) spray control system can vary application rate while maintaining a constant spray pattern and droplet spectrum. Gopalapillai et al. (1999) evaluated a Synchro flow control system consisting of PWM solenoid valves attached to each nozzle. The control system operated solenoid valves at 10 Hz and duty cycles of 10% to 100% to control the flow rate. It was observed that the control system could vary the nozzle flow rate at a ratio of up to 9.5:1 with significant change in the spray pattern. They found that the volume mean diameter at a duty cycle of 10% was significantly different from the 25%, 50%, 75% and 100% and uniformity of spray deposition along the orthogonal direction decreased dramatically as the duty cycle decreased and travel speed increased.

2.3 PRECISION AG TECHNOLOGIES

Control systems have become an integral part of new precision agriculture (PA) technologies. These technologies use GPS receivers for machine guidance, thereby helping equipment operators to achieve greater productivity by reducing overlap between adjacent passes. In addition to guidance, GPS receivers provide position and vehicle speed data for control decisions, real-time display of a farming operation, and recording of valuable as-applied data for downloading from a controller. The operator can also upload field boundaries and desired application maps into controllers to perform uniform or variable-rate application (VRA) using an appropriate flow control system.

2.3.1 VARIABLE-RATE TECHNOLOGY

Agricultural fields may not require uniform application of nutrients due to spatial variability of soil type, organic matter, yield and weed/pest. Therefore, application rate of chemicals are varied by recognizing specific needs of distinct areas in the field using variable rate application (VRA) technologies for both map-based and sensor-based applications. For map-based applications, VRA of pesticides and nutrients is performed by changing application rates as a function of vehicle spatial location based on GPS location and map prescription rate. These technologies manage the spray application on a much finer resolution when compared to whole field basis (Fulton et al., 2001). Past research on the response and accuracy of rate controllers conducted on VRA were completed to minimize chemical handling by the operator, select rate on-the-go and reduce excess chemical application. A study by Carrara et al. (2004) on VRA of herbicide concluded that even with significant variability of weed distribution, VRA resulted in almost even grain yield over the entire field and saved almost 29% of herbicides compared to the conventional farming system. Many researchers indicated up to 60% saving in herbicide when implementing map-based VRA (Haggar et al., 1983; Johnson et al.,1995). Yang (2001) conducted static and dynamic performance of a VRA applicator for side dressing of two different liquid fertilizers. The dynamic results indicated that VRA system stabilized at the desired rate within 1 to 2 s and the mean application rate errors for two fertilizers were 2.5 and 5.2% in 1997 and 2.8 and 5.8% in 1998. Thus, VRA of fertilizer has the potential to increase yield, reduce yield variability, and improve economic returns (Yang et al., 2001).

Map-based VRA application of nutrients can be based on a variety of criteria including soil sampling and yield monitor data. However, research and technological advances in the field of crop canopy sensing have greatly enhanced the ability to use crop sensing instruments. For crop sensing, optical sensors are being used to measure in-season crop conditions to better predict nutrient requirements or crop stress. Both map-based and real-time sensor-based systems can be used for spray application by utilizing in-season information gathered from crop sensors. Many researchers currently use the normalized difference vegetative index (NDVI), which is based on a red or near-infrared (NIR) sensor (Mullen et al., 2003; Raun et al., 2002) like the Greenseeker™ and Crop Circle™ to decide nutrient application rates; primarily nitrogen to-date. Crop sensing can be promising since it provides a more direct measure of plant nitrogen needs compared to soil tests and yield monitors (Biermacher et al., 2009). Li et al. (2009) evaluated optical sensor-based, in-season nitrogen management and reported that crop-sensor based management strategies increased nitrogen use efficiency (NUE) up to 61.3% as compared to 13.1% with conventional practices.

The response time of real-time, sensor-based, VRA is however critical in achieving target application rates when using existing control systems. Bennur and Taylor (2010) evaluated the response time of commercially available rate controller using a pulse width modulated system (PWM) system with fixed orifice nozzles and a standard system using a fast close (FC) valve with variable-rate orifice nozzles. The authors indicated that the response time of PWM- and FC-applicator using simulated ground speed and map based application input using VRT varied between 0.5 and 2.1s. They further concluded that for each applicator, configuration response time should be established to achieve optimum performance for VRA when using a real-time sensor-based system.

2.3.2 AUTOMATIC SECTION CONTROL TECHNOLOGY

Among the wide variety of rate control systems, some of them have automatic section control (ASC) technology which automatically controls shutting ON or OFF boom or nozzle control sections (Figure 2.5). The control system with ASC technology uses boom shut-off valves or nozzle solenoids, in addition to a GPS receiver, to shut ON or OFF selected boom- or nozzle-section(s). The controller automatically shut-off boom- or nozzle section(s) in previously sprayed areas such as headlands or no-spray areas such as grass waterways, thus can save on input costs while reducing overlap areas.

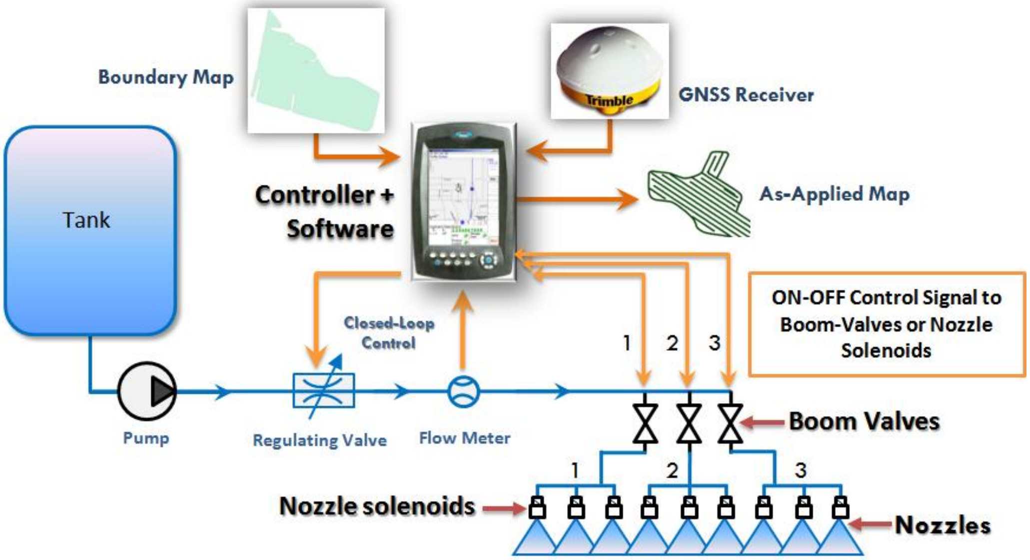


Figure 2.5. Overview of the typical components and setup for a sprayer equipped with automatic section control.

The rate controller with ASC can efficiently turn ON or OFF control sections as compared to the operator making that decision. However, these system using flow-based rate controllers additionally monitors control section spatial location w.r.t to boundary map, manage control section OFF and ON state (Figure 2.6), calculates spray swath width, and generate as-applied map apart from managing system flow. The system flow is managed through a closed loop control and feedback involving flow meter, regulating valve and controller.

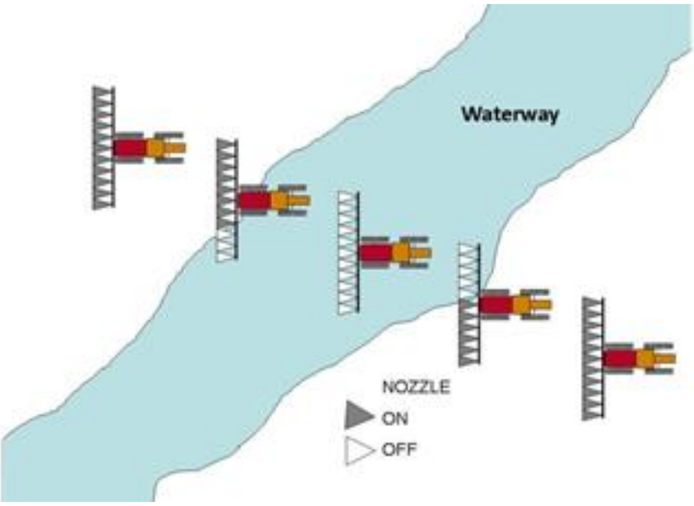


Figure 2.6. Illustration of auto-nozzle control when a sprayer traverses a grassed waterway.

2.3.3 BENEFITS OF AUTOMATIC SECTION CONTROL

Under- and over-application of pesticide can be a problem when managing spray applications. Under-application of chemical may not be sufficient to effectively control pests (Hoehne and Brumett, 1982) thereby possibly resulting in yield loss and development of chemical resistant among pests. Further, additional application if the first was not effective would add fuel, labor and chemical cost. Over-application of chemical on the other hand only increases input costs, in addition to potential chances of crop damage and environmental pollution by way of run-off to water bodies (Grisso et al., 1989; Miller and Smith 1992). Luck et al. (2010a) studied the potential of nutrient and pesticide saving using map base ASC of spray nozzles. They reported that a reduction of 15.2% to 17.5% in area applied to each field when using map-based ASC. The additional benefit was the reduction in frequency of loading inputs into the sprayer as less material was wasted during spray application. In another study, Luck et al. (2010b) reported that adding ASC for control sprayer boom-section significantly decreased the over-application from 12.4% to 6.2%. The results highlighted that reduction in over-application directly reflected the savings to the producers. Over-application can be greatly reduced especially as the no-spray zones (grassed waterways) increased by switching from manual control to ASC.

2.3.4 ISSUES

Precision agriculture approaches on spray technology have assimilated numerous new control strategies with the existing control systems but this integration should have a timely response to changing system rate requirements (Rietz et al., 1997). Though, control systems have greatly reduced off-target chemical application, with increasing controls and feedback demands on the current systems, the concerns regarding response time are critical. During a system flow rate control routine, two types of time lags exist: 1) control system response and lag time and 2) dynamic nozzle flow rate stabilization due boom configuration. The first lag time represents time between a control system reading a control command based on the GPS vehicle location, reading the system flow rate, sending appropriate control signal and achieving stable intended system flow rate. Second time lag occurs while the boom system is readjusting from present state to the new introduced step change and emerging boom dynamics. Though studies have been conducted to quantify chemical concentration lag times associated with injection control system and performance of ground driven sprayer using pressure-based control system; research needs to be done on flow control system equipped with ASC technology to quantify system lag time and nozzle flow response during ASC actuation.

The response time of each hardware component of the control system can also have an impact on accuracy and efficacy of the overall system. Vogel et al. (2005) evaluated a variable-rate sprayer, attaining automatic product shut-off using a fast-close ball valve. They determined that rate changes usually consisted of a smooth increase or decrease in herbicide rates, except an application rate spike occurred while using the fast-close ball control valve, in situations when the prescribed rate changed from OFF to ON. The fast ball control valve produced flow rate spikes that reached as high as 450 L/ha (from the actual application rate of 300 L/ha) between the current and new target rates. These rate spikes highlighted that flow response during rate changes can impact nozzle flow during chemical applications. Therefore, there is a need to undertake a systematic study to determine flow control hardware response characteristics when using ASC technology.

2.4 SUMMARY

With increasing costs of chemicals, the demand for accurate and timely spray application is higher than ever. Producers are managing more acres and do not want to incur losses due to over- or under-application of crop inputs since profit margins are declining. Producers have embraced advanced spraying technology to better manage the application of crop inputs. Industry responded to the growing demand for self-propelled sprayers of increasing width by recently developing an array of new controls, touch screen consoles, and real-time wireless data management. However, little research has been conducted to ascertain adequate setup, calibration and efficiency of spray applicators with modern flow control technologies. Research is needed to understand control system response, hydraulic dynamics within the boom plumbing and how components impact application accuracy when using new technologies. The knowledge gained from this study will not only help to further improve existing technology but will build confidence in producers' adopting these technologies to better manage crop inputs, increase profits, and reduce environmental impacts of chemical and nutrient applications.

CHAPTER 3

APPLICATION UNIFORMITY AND ACCURACY OF TWO AUTOMATIC SECTION CONTROL SYSTEMS ON AGRICULTURAL SPRAYERS

3.1 ABSTRACT

The adoption of automatic section control (ASC) on agricultural sprayers remains popular since it reduces overlap and application in unwanted areas leading to input savings and improved environmental stewardship. Most spray controllers attempt to maintain the desired target rate during ASC actuation (change in width) but limited knowledge exists regarding controller response and nozzle discharge variation during field operation. Therefore, an investigation was conducted to evaluate the impact of controller response on maintaining target application rates. Field experiments were conducted using two common self-propelled sprayers equipped with commercially available control systems with ASC capabilities (Sprayer-1 with standard boom-section control and Sprayer-2 with nozzle-control). Pressure transducers were mounted across the spray booms to record real-time nozzle pressure with data tagged with GPS location and time. Nozzle pressures were used as a proxy to obtain nozzle flow rates using manufacture pressure-flow data. The resulting flow rates were used to compute nozzle uniformity across the boom (CV), off-rate errors and settling times. Results indicated that nozzle CVs were greater than 10% for both auto-boom and auto-nozzle control systems, when each of the auto-boom and auto-nozzle sections were turned back ON for 0.5 s and 0.2 s, respectively. Nozzles in those sections turned OFF continued to spray for up to 3.5 s for the auto-boom and 0.2 s for the auto-nozzle sprayer. Nozzle off-rate errors exceeding ±10% occurred in both rectangular and irregular shaped fields. Sprayer acceleration with simultaneous ASC actuation contributed to under-application; whereas ASC actuation and deceleration resulted in over-application regardless of ASC (nozzle or boom-section) technology. Ground speeds less than 16.1 km/h with ASC actuation resulted in unexpectedly high nozzle

flow settling times (> 20 s) for the auto-nozzle sprayer during static tests. Extended settling times of the control system contributes to nozzle off-rate thereby impacting overall application accuracy. Finally, static tests can be used to draw realistic conclusions of in-field sprayer performance thereby reducing field testing time.

3.2 INTRODUCTION

Boom widths for agricultural sprayers continue to increase in the US. It is not uncommon to see widths of 36.6 m being used today along with ground speeds nearing 30 km/h to cover cropland in a timely fashion. This increase in application width coupled with varying field shapes and sizes, commonly found in the southeastern US, demand stable and quick control response to minimize off-rate errors during field operation. Past surveys on U.S. farms, including those of private herbicide applicators, indicated that more than 50% of sprayers deviated beyond 10% of target application rate largely due to worn nozzle tips, inaccurate calibration, or inability to maintain the required flow rate during field application (Gerling, 1985; Grisso et al. 1989; Hofman and Solseng, 2004). Spray rate controllers have been implemented over the years on agricultural sprayers to appropriately manage application rates during field operation. Initially, these controllers compensated for sprayer acceleration and deceleration to maintain a constant application rate thereby maintaining the desired target rate. A ground speed sensor and a pressure transducer provided feedback to the control system which adjusted the opening or closing of the flow control valve. Pressure based spray control systems were able to maintain the target rate within 5% during ground speed variations from 3.2 to 9.7 km/h (Ayers et al. 1990). Further, these control systems typically have used a ground radar sensor for speed determination (Tompkins et al., 1988; Khalilian et. al., 1989) and reduced the application errors from -18% and 5% down to -7% and 1% when compared to ground driven systems (Al-Gaadi and Ayers, 1994).

Today, most if not all spray controllers on large self-propelled sprayers manage system flow and not necessarily the overall system pressure. These control systems attempt to maintain the target rate regardless of width (sections or nozzles ON) and/or ground speed changes. However, the accuracy of managing the application rate depends on controller responsiveness along with the resolution of the flow meter to maintain the required flow rate at any point in time. The number of agricultural sprayers equipped with ASC technology has increased over the past several years. ASC technology turns individual boom-section valves (auto-boom control) or nozzle solenoids (auto-nozzle control) OFF when traversing a no-spray area or previously sprayed area, and back ON in non-sprayed areas of fields. This technology has demonstrated considerable potential to reduce input application overlap (Batte and Ehsani, 2006) resulting in savings on inputs. Luck et al. (2010a) indicated ASC reduced overlap down to 6.2% as compared to 12.4% when compared to manual control by the operator. Additionally, the coverage area for a field can be reduced between 15.2% and 17.5% when using ASC in irregular shaped fields (Luck et al., 2010b). However, an additional concern exists about control systems incorporating ASC technology for large agricultural sprayers with regard to spray application accuracy during field operating conditions.

Rate control systems have inherent time delays when rate adjustments are required during field application. Previous research indicated 12.0 to 38.3 s delay times for direct chemical injection when changing concentration rates (Tomkins et al., 1990; Sudduth et al., 1995; Sui et al., 2003). It has also been documented that a 27.4 m wide sprayer using direct injection traveling at 24.1 kph produced a 12 s response delay resulting in just over 2,200 m2 of misapplication (Tomkins et al., 1990). The control system latency in responding to the differential global positioning system (DGPS) receiver while maintaining a horizontal accuracy of 1 m can be up to 2.2 s (Al-Gaadi and Ayers, 1999). Apart from the control system and GPS response time delays, Rietz et. al., (1997) reported that some flow based control systems tend to over apply when only one boom-section was spraying. Grisso et al. (1989) along with Miller and Smith (1992), reported that lateral location of nozzles along the boom can also impact the magnitude and temporal occurrence of application rate errors.

Previous research has stated precision farming approaches should have control systems with timely response to changing system rate requirements (Rietz et al., 1997). ASC evaluations during static testing indicated that nozzle pressure variation can range from 6.7% to 20.0%, which equated to an increase of 3.7% to 10.6% in nozzle flow (Sharda et al., 2010). Additional ASC testing demonstrated nozzle pressure stabilization times approached 25.2 s for auto-boom and 15.6 s for auto-nozzle control when turning sections OFF then back ON. Increased nozzle pressure and delayed pressure stabilization times have indicated that application variability can occur when manually turning sections ON/OFF or implementing ASC. It has been reported that nozzle pressure deviation from -28% to +29% can occur during point row operation resulting in -19.2% to +12.4% deviations in nozzle flow (Sharda et al., 2009). The disparity in dynamic pressure response and off-rate errors indicated that differences existed between boom-section and nozzle control. The delayed nozzle flow stabilization times during ASC also highlighted inadequate feedback to the control system. Specifically, this occurred when sections turned OFF or ON faster than the designed feedback and response time to accurately manage the desired target application rate. While ASC provides benefits to those adopting the technology, the static tests simulating real field scenarios highlighted that continuous ON/OFF actuation of nozzles can cause pressure variations across the boom (Sharda et al., 2010) leading to over- and under-application. The extent of these errors can escalate when spraying in irregularly shaped fields plus using larger sprayers.

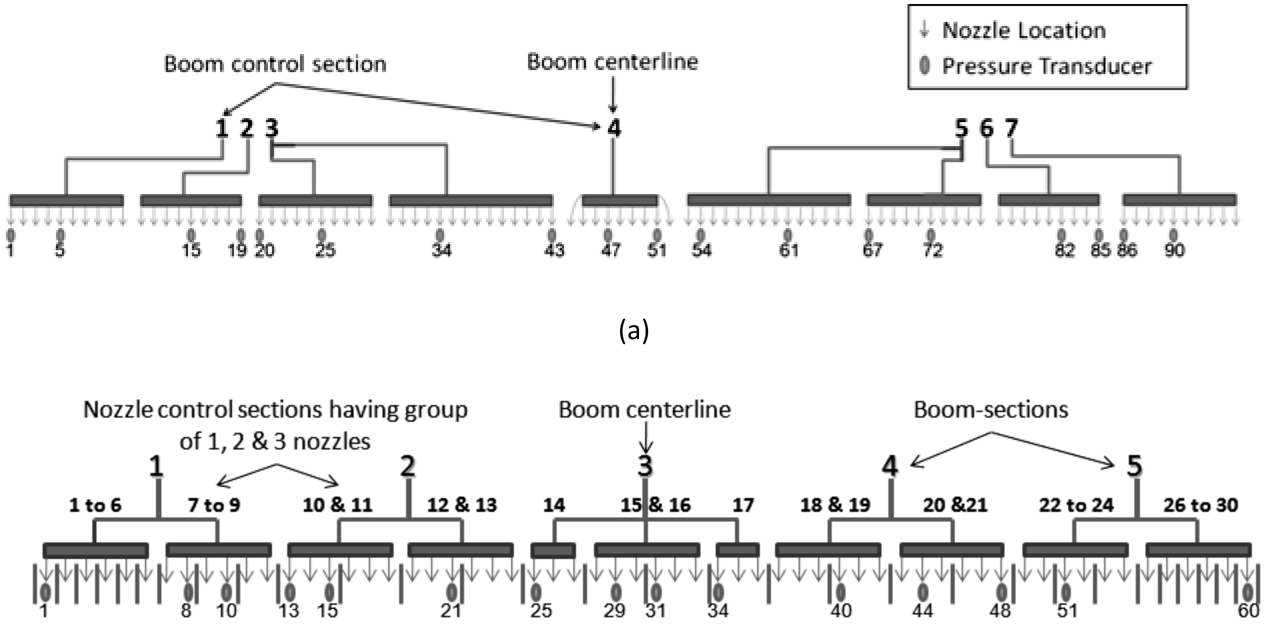
Though attempts have been made to report flow control hardware time lags, research is needed to understand nozzle flow uniformity and application rate stability when using precision technologies such as ASC. Comparison of static and field test results can aid in predicting field performance of large agricultural sprayers and also in formulating experimental design which can accelerate the process of quantifying nozzle uniformity and application rate stability. Therefore, the objectives of this investigation were to: 1) evaluate real-time nozzle uniformity (CV) across the boom for two ASC systems, and 2) quantify and compare nozzle flow settling times and off-rate errors during static and field testing.

3.3 MATERIALS AND METHODS

Static and field experiments were conducted using two common self-propelled sprayers (Figure 3.1) referred to as Sprayer-1 and Sprayer-2 here forward. The sprayers were equipped with commercially available rate controllers with ASC capabilities. Sprayer-1 was equipped with auto-boom control (Figure 3.1a) while Sprayer-2 (Figure 3.1b) with auto-nozzle control. Sprayer-1 was a 36.2-m wide, wet-boom sprayer with 95 nozzles spaced at 38-cm across the boom. This sprayer was set up with seven boom sections with the ON/OFF control provided by the seven existing boom section valves. There were 10 nozzles on boom-sections 1 and 7; nine nozzles on boom-sections 2, 4 and 6; and 24 nozzles on boom-sections 3 and 5 (Figure 3.2a). Sprayer-2 also had a wet-boom setup applying 30.5-m wide. It had 60 nozzles spaced at 51-cm. Auto-nozzle control was obtained using solenoid valves (Capstan Ag Systems, Inc., Topeka, Kansas, USA) mapped within the controller such that the six outer nozzles on each side were controlled individually, the next six inner nozzles on either side coupled, and the remaining controlled in groups of three (Figure 3.2b). Both sprayers were also equipped with auto-guidance systems.

(a) (b)

Figure 3.1. Illustration of Sprayer-1 (a) and Sprayer-2 (b) used during this investigation.



(a)

(b)

Figure 3.2. Layout of for Sprayer-1 containing seven individual boom-sections (a) and Sprayer-2 which included 30 nozzle sections of either one, two or three nozzles. Sections are numbered from left to right for both booms with the nozzle location along the boom numerically identified.

3.3.1 FIELD TESTS

Field experiments were conducted with the target rate set at 93.5, 112.1 and 140.2 L/ha for Sprayer-1 and at 93.5 and 140.2 L/ha using Sprayer-2. Sprayer-2 was used to collect application data for three irregularly shaped fields consisting of numerous no-spray areas; mostly grassed waterways. The field experiments using Sprayer-1 were conducted on rectangular and triangular fields. High frequency (≤1ms response time) pressure transducers (Model 1502 B81 EZ 100 PSI G, PCB Piezotronics Inc., Depew, N.Y., USA) with an accuracy of ≤0.25% full scale were mounted across the spray booms (Figure 3.3) to record nozzle pressure. Eighteen transducers were used for the Sprayer-1 and 15 for Sprayer-2 (Figure 3.2). Transducers were mounted such that at least two were located within each section based on the existing plumbing (Figure 3.2). For both sprayers, one pressure transducer was mounted on the main supply line (location for the existing pressure transducer providing feedback to the controller), to measure the overall system pressure. A data acquisition system consisting of National Instruments boards was used to read and record all data at a 5 Hz sampling frequency during field tests and at 50 Hz during static tests. Position and ground speed data were collected simultaneously and provided by a sub-meter GPS receiver (Ag132, Trimble Navigation Ltd., Sunnyvale, CA, USA) for Sprayer-2 and a GNSS RTK receiver (R8 rover and R7 base with the Trimmark 3 radio transmitter; Trimble Navigation Ltd., Sunnyvale, CA, USA) for Sprayer-1. All data were recorded to a text file for analyses.

Figure 3.3. Pressure transducer mounted at a nozzle.

Nozzle (Teejet AI11003 for Sprayer-1 and Teejet TT11005 for Sprayer-2, Spraying Systems Co., Wheaton, IL, USA) pressures were converted to flow using the manufacture data (Teejet Catalog 50A, Spraying Systems Co., Wheaton, IL, USA). The actual application rate (L/min) was calculated by summing and averaging the nozzle flow rate from those sections remaining in the on-state at each GPS time stamp. The coefficient of variation (CV) was calculated considering only ON sections, which represents nozzle flow uniformity across the boom. The target nozzle flow for each GPS time stamp was calculated using the number of ON sections (or nozzles) along with the ground speed and target application rate (set by the operator). The display console on Sprayer-2 also recorded a time stamp along with control channel state (ON = 1 or OFF = 0) for each GPS coordinate at a sampling frequency of 5 Hz. The files containing the control channel state and spatial pressure data were synchronized and merged using the GPS time stamps within these files. The control section status was used to calculate spray width at each GPS point. For Sprayer-1, the system pressure and mean nozzle pressure in each section was used to determine the on/off state of a boom valve using MATLAB (version R2008a). The mean nozzle pressure for ON sections was found to be within ± 5% of the system pressure. Therefore, for any boom-section in the on-state, a less than -5% difference between mean nozzle pressure and system pressure would mark that section being OFF at that time stamp. Similarly, if the initial state of the boom-section was OFF, then an average nozzle pressure of greater than 34.5 kPa at any time stamp would result in an on-state. Finally, the overall nozzle off-rate (rate error) was calculated as a percent difference from the target rate using the following equation:

$$\text{Overall nozzle off-rate (\%)} = \frac{(Actual\ nozzle\ flow\ rate - target\ nozzle\ flow\ rate) * 100}{(target\ nozzle\ flow\ rate\ )} \qquad (1)$$

Nozzle flow rate uniformity (CV) was evaluated by computing the mean and standard deviation of all the ON nozzles or boom sections. During field and static testing, ±10.0% rate errors were considered acceptable for nozzle off-rate (Rietz et al., 1997). Finally, off-rate and CV maps were generated using ESRI’s ArcMap 9.3 to illustrate spatial results across fields and select example scenarios for further investigation.

3.3.2 STATIC TESTS

A 93.5 L/ha target rate and simulated ground speeds of 16.1 and 24.1 km/h were selected for evaluating Sprayer-2. Since Sprayer-1 was unable to simulate different ground speeds, system pressures of 138, 276, 414 and 552 kPa at a constant 19.3 kph were selected for conducting the static tests. Experiments were conducted by; 1) turning individual sections ON and OFF (both sprayers); 2) sequentially turning all sections OFF and back ON at 1s and 5s intervals (both sprayers); and 3) varying machine acceleration from 6.4 km/h to 29.0 km/h and deceleration returning to 6.4 km/h (Sprayer-2 only). During each test, selected sections were turned OFF until nozzle flow stabilized, then the selected sections were turned back ON. The mean nozzle flow using only the ON nozzles was used to calculate off-rate and nozzle flow settling time (ST).

Overall nozzle off-rate represented application rate stability during the various static and field tests and therefore provided the extent of over- and under-application. To understand the effect of sprayer acceleration and ASC actuation, specific ASC actuation scenarios (i.e. headland and point-rows operation) were identified and analyzed. The term ‘reentry’ implied the sprayer was entering into a spray zone while ‘exiting’ refers to the sprayer moving out of a spray zone. In these examples, the seven individual boom-sections for Sprayer-1 were illustrated as gray polygons, the initial passes around the field boundary as green cross-hatched regions, and areas covered as each section was ON with as blue shaded regions. MATLAB was used to compute nozzle flow rate variables including: target rate, final rate, off-rate percentage and ST. ST represented the time difference between a ±5% (ST5) or ±10% (ST10) differential from the initial nozzle flow and when the nozzle flow finally reached and stayed within ±5% or ±10%of the final nozzle flow rate. Both ±5% and ±10% off-rate was used for determining the ST since static tests were completed with the spray boom stable on level ground. Therefore, under these controlled conditions, nozzle off-rate was evaluated using ±5% threshold while the ±10% was included as the industry-referred criteria.

3.4 RESULTS AND DISCUSSION

Field experiments using Sprayer-1 (auto-boom) demonstrated that nozzle CVs above 10% and nozzle flow rates beyond ±10% (Figure 3.4) of the target rate occurred occasionally but, were mostly clustered at the field headlands. These errors were attributed to rate controller adjustments to compensate for sprayer acceleration and deceleration but at times speed changes. ASC actuation of individual sections was minimal for this field because of its rectangular shape, with nearly all sections turned ON or OFF, simultaneously. The off-rate was well within ±10% of the target rate since operating conditions were stable (e.g. constant ground speed and all sections ON) for the majority of field application. However, this example field highlights undesirable spray nozzle performance resulting from control system lag time. This outcome should be considered by the operator along with the design of the sprayer and control system.

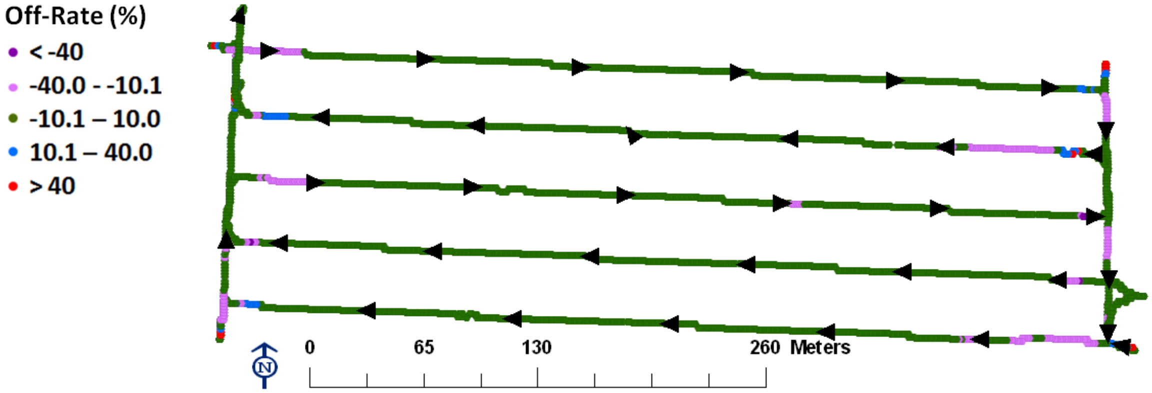
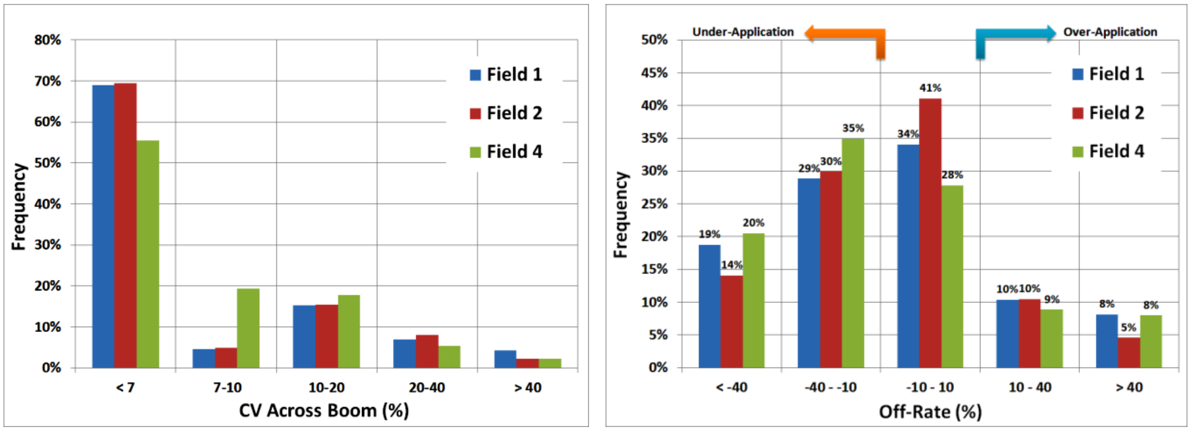


Figure 3.4. Nozzle off-rate map during application at 93.5 L/ha in a rectangular field using Sprayer-1. Black arrows represent direction of travel.

Sprayer-2 results indicated that nozzle CVs were greater than 10.0% for 26.0% of the time (Figure 3.5a) and off-rates beyond ±10.0% for 66.0% of the time (Figure 3.5b) in irregular shaped fields. Nozzle CVs and off-rate results were somewhat comparable (Figure 3.5) even though these fields varied in area and shape. CVs exceeding 10% occurred when exiting and reentering spray zone and ASC actuation.

Both situations affect lateral spray distribution resulting in non-uniform coverage. The nozzle CVs were less than 10% during stable operating conditions which suggested the nozzle tips were in good condition. Nozzle flow rates were below -10% (under-application) for 49% of the time, typically when reentering spray zones, and were above +10% (over-application) for around 17% of the time (Figure 3.6). These results suggested that under-application occurred more frequently (greater percentage of time) than over-application in these fields. Over-application can typically result in unwanted expense, potential crop damage and/or carryover whereas; under-application can lead to ineffective pest control, all of which reduce net farm income.



(a) (b)

Figure 3.5. Distribution plots for nozzle CV (a) and off-rate error (b) for three fields using Sprayer-2.

ASC actuation occurred more than 63.2%, 65.5% and 77.9% of the time in fields 1, 2 and 4, respectively (Figure 3.7a). Ground speeds for fields 1, 2 and 4 were within 16 to 24 km/h range for 63.1%, 51.7% and, 41.7% of the time, respectively (Figure 3.7b). The ground speed changed as the operator maneuvered within field boundaries which included grassed waterways and obstructions (electricity poles and sink holes). This led to sprayer acceleration and deceleration beyond ±0.5 m/s^2 for 26.6%, 23.8% and 29.6% of the time in the field 1, 2 and 4, respectively. The ASC actuation (number of nozzles ON) and speed distribution maps (Figure 3.8) indicated that the system flow rate changed more frequently than expected during field application. Further, a tremendous demand was placed on the rate controller to quickly manage system flow rate changes during ASC actuation and/or ground speed changes. In these cases, it took time for the control system to achieve the required system flow rate (Figure 3.8). Overall, nozzle off-rate occurred to some extent for both Sprayer-1 and Sprayer-2 with operation outside preferred levels being problematic. These off-rate errors should be corrected to maintain target rates at the nozzles and preserve the desired product efficacy.

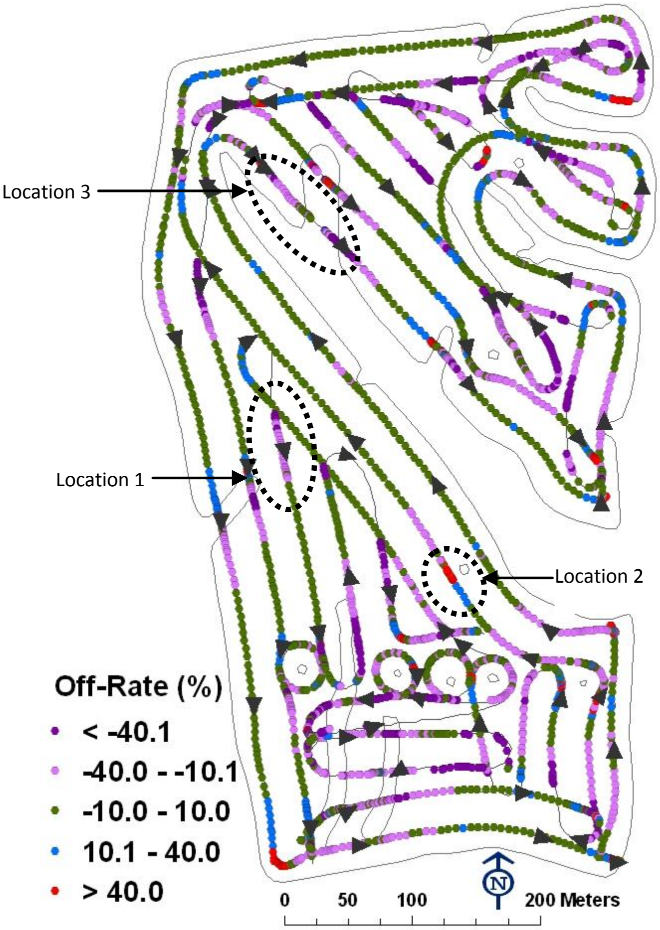
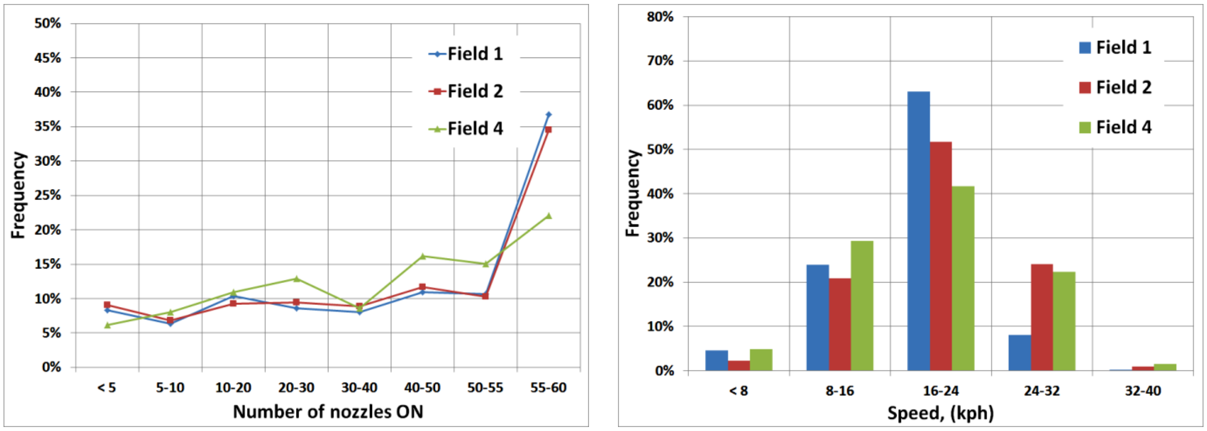
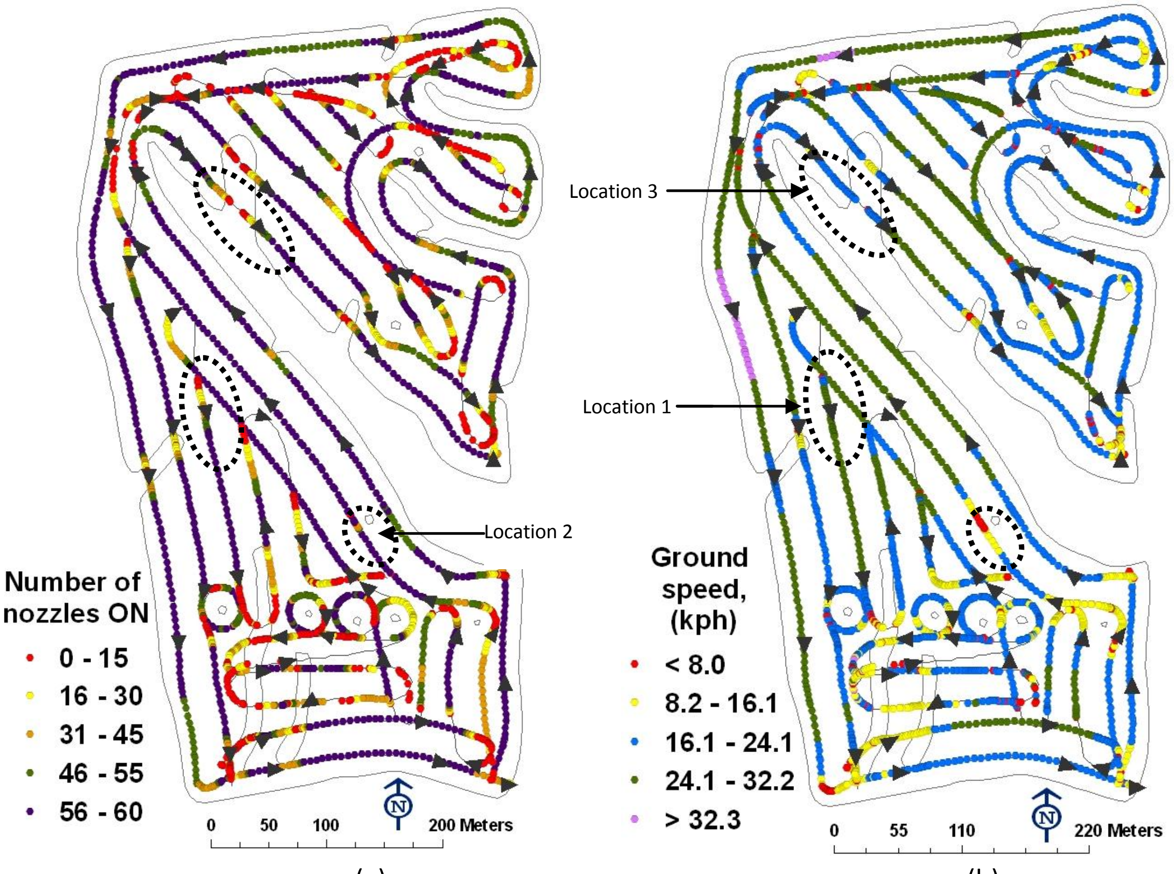


Figure 3.6. Nozzle off-rate map for Field 2 using Sprayer-2 with travel direction indicated by black arrows.



(a) (b)

Figure 3.7. Distribution plots for the number of nozzles on (a) and ground speed (b) for each of the three fields when using Sprayer-2.



(a) (b)

Figure 3.8. Application maps for Field 2 illustrating: a) number of nozzles on and b) ground speed along with travel direction (black arrows) for Sprayer-2.

3.4.1 ERRORS FROM ACCELERATION – FIELD TESTS

An example reentry scenario was selected from Field 2 (Location 1 Figure 3.8) to demonstrate control system response and the potential extent of off-rate application for Sprayer-2. During reentry at a 30° angle of incidence, system flow increased from 5.6 to 126.3 Lpm as the sprayer accelerated from 8.0 to 26.9 km/h with nozzle sections 4 through 30 turning ON. The results indicated nozzle CVs greater than +10.0% and the off-rate error was up to -40% (Figure 3.6, Location 1). High CVs across the boom were found to be associated with nozzles or nozzle sections turning back ON and were possibly due to system noncompliance when the plumbing (e.g. hoses and tubing) refilled as sections were turned back ON. Therefore, each time a control section changed from off to on states, the nozzle CVs exceeded +10% for around 0.2 sec. This example demonstrates that Sprayer-2 traveled about 64 m before the controller was able to achieve an appropriate system flow rate as nozzle sections were turned ON and the sprayer was accelerating.

A similar scenario was investigated for Sprayer-1 (

Figure 3.9). Here, the sprayer accelerated from 5.7 kph to 20.7 kph while boom-sections 1 through 7 were sequentially turned ON as it reentered the spray zone at 40° angle of incidence. Results indicated that nozzle off-rate error was up to +164.9% when sections 1 through 3 turned ON and up to -46.5% when sections 4 through 7 turned ON. Nozzle off-rate errors occurred for almost 60 m before stabilizing within ±10.0% of the intended rate. These results for Sprayer-1 were comparable to those found with Sprayer-2 when accelerating and reentering the spray area.

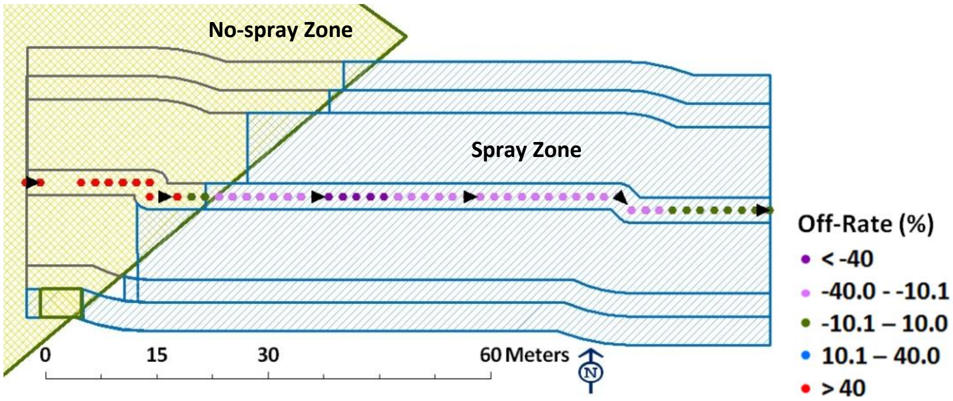


Figure 3.9. Example scenario of Sprayer-1 accelerating and ASC actuation as it reenters (sections turning ON) the spray zone when applying at a target rate of 140.2 L/ha.

3.4.2 Errors from Deceleration – Field Tests

The effect of deceleration on nozzle off-rate error was observed in several instances for both sprayers. Location 2 (Figure 3.6 & Figure 3.8) depicts nozzle CVs and flow rate response for Sprayer-2 while decelerating accompanied by section turning OFF. The sprayer decelerated to maneuver around an electricity pole at this location. Here, the required system flow rate decreased from 85.2 to 11.7 Lpm as the sprayer slowed from 18.7 to 3.2 kph (Figure 3.8b, Location 2). As the sprayer approached the pole at Location 2, almost all nozzle control sections were ON until 11 control sections were turned OFF as the sprayer maneuvered around the obstacle. This scenario demonstrated off-rate errors up to +120% for Sprayer-2.

The scenario in Figure 3.10 illustrates an example of Sprayer-1 decelerating from 24.3 to 7.4 kph while exiting a spray zone. The off-rate map (Figure 3.10) demonstrated that deceleration resulted in off-rate errors up to +50% for Sprayer-1. Sprayer-1's deceleration continuously demanded a new system flow rate during these dynamic conditions and suggests potential feedback and response limitations for the rate controller. It was interesting to note that during these two scenarios, nozzle CVs were within 7.0% as they sprayers decelerated, indicating uniform deposition across the boom.

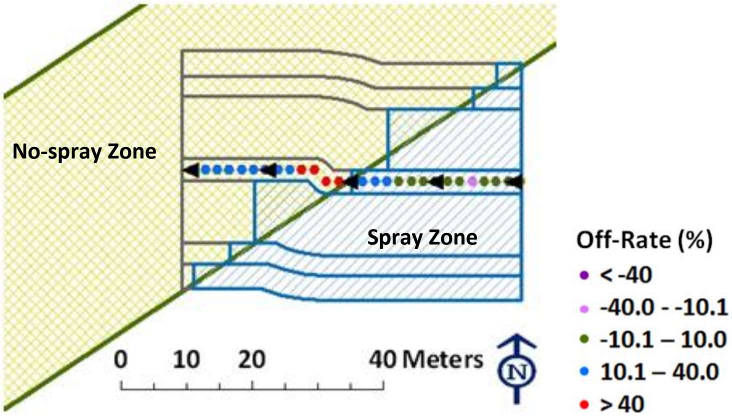


Figure 3.10. Example of Sprayer-1 decelerating while exiting (sections turned OFF) a spray zone into a previously applied area when applying at a target rate of 93.5 L/ha.

3.4.3 ACCELERATION AND DECELERATION - STATIC TEST RESULTS

Static tests for Sprayer-2 revealed that accelerations generated deviations between -7.8% and 7.4% from the target application rate (Table 3.1). Similar, but larger in magnitude, nozzle off-rate between -7.5% and 37.2% occurred while decelerating. An interesting note, ground speeds less than 16.1 kph resulted in positive overall nozzle off-rate while speeds greater than 16.1 kph resulted in negative values. The overall nozzle flow settling times ST5 during acceleration and deceleration varied from 5.6 to 20.8 sec (Table 3.1). The static tests highlighted that although the final nozzle off-rate was within ±10% (except for the 9.7 to 6.4 kph test), the STs were unexpectedly long. The speed change tests were conducted under controlled operating conditions but the ST5 and ST10 results indicated a delayed response at the nozzle. All ST5 values were above 5.6 s which indicated that frequent acceleration and deceleration can result in off-rate errors at the nozzle. These STs and nozzle off-rate errors were expected based on the maps (Figure 3.6 and Figure 3.8b) generated for Sprayer-2 during acceleration and deceleration. Nozzle flow STs also decreased during acceleration and increased during deceleration which was expected and observed in the field results.

Table 3.1. Mean nozzle off-rate and flow settling times (ST) during simulated static acceleration and deceleration tests.

Acceleration				Deceleration			
Speed change (kph)	Off-Rate Error (%)	ST5 (s)	ST10 (s)	Speed change (kph)	Off-Rate Error (%)	ST5 (s)	ST10 (s)
6.4-9.7	7.4	20.5	12.8	29-25.7	-6.4	5.6	*
9.7-12.9	6.5	19.0	11.7	25.7-22.5	-4.7	7.3	1.6
12.9-16.1	0.9	10.2	2.9	22.5-19.3	-7.5	7.0	1.5
16.1-19.3	-2.0	7.0	0.9	19.3-16.1	-5.1	8.2	2.7
19.3-22.5	-3.5	7.5	1.3	16.1-12.9	4.7	20.8	15.3
22.5-25.7	-5.8	6.2	0.1	12.9-9.7	9.9	20.4	#
25.7-29.0	-7.8	6.0	*	9.7-6.4	37.2	20.0	14.8

ST5 = Nozzle flow rate settling time considering ±5% of intended and final rate.
ST10 = Nozzle flow rate settling time considering ±10% of intended and final rate.
*= The initial and final flow rate within ±10% of initial and final nozzle flow rates
#=The final flow rate did not settle within ±10% of final intended rate

The steady-state nozzle flow oscillated around the target rate below 16.1 kph (91.7 L/min). This flow oscillation or instability could be due to fact that the control system attempted to quickly compensate, but was continuously over-shooting the intended set point. This over-compensation contributed to unexpectedly longer STS and off-rate errors which reached +37.2%. Similar off-rate errors were observed during sprayer deceleration at Location-2. It is important to note that acceleration from 6.4 to 9.7 kph required a 50% increase in nozzle flow whereas a speed change from 25.7 to 29.0 kph required only a 12.5% increase. Hence, the control system response (Table 1) may be impacted by the required magnitude of flow adjustment, control system configuration, and sprayer acceleration or deceleration.

3.4.4 ERRORS FROM ASC ACTUATION – FIELD TESTS

Scenarios for Sprayer-1 (Figure 3.11) and Sprayer-2 (Location 3, Figure 3.6) were selected to illustrate the effect of ASC actuation on off-rate error. For these scenarios, the sprayers traversed no-spray zones (grassed waterways) where sections were sequentially turned OFF then ON at a ground speed of 24 kph. The nozzle off-rate was up to -65% for Sprayer-1 and -68% for Sprayer-2 during ASC actuation in these areas. Nozzle CVs were greater than 10% for a short duration (0.2 to 0.4 s) when reentering the spray area. In general, the maps depicted that ASC actuation resulted in more negative off-rate or under-application during these scenarios. Under-application can result from feedback or control system response delays for e.g. the resolution and shorter response time of flow meter can give accurate and quick feedback to the controller to implement rate management strategies. Further the approaches used to manage response of control hardware can significantly impact application accuracy. The control system can appropriately look ahead and might include robust algorithms to access the magnitude of rate change required. This assessment can be used to select a dynamic response algorithm to reduce the delay in pressuring the hoses, minimize application rate errors and quickly achieve stable conditions. Finally flow control point (e.g. boom-valve) can be moved as close to the boom-section as possible to lower transient off-rate errors.

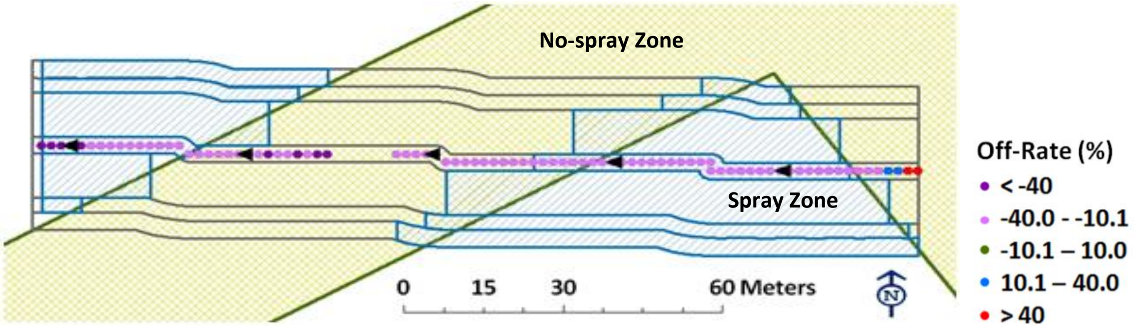


Figure 3.11. Example scenario in which Sprayer-1 was entering and then exiting a no-spray zone (sections turned OFF and ON) while operating at 24 kph. A target rate of 140.2 L/ha was set in the controller and the nonexistence of off-rate symbols represents all sections in the off-state.

3.4.5 ASC ACTUATION – STATIC TEST RESULTS

During static testing, nozzle off-rate errors during ASC actuation were up to -31.8 % for Sprayer-2 (Figure 3.12). Nozzle flow analyses for Sprayer-2 showed that the control system responded quickly during required rate changes but the actual nozzle flow was less than the target. Frequently, the control system on Sprayer-2 was unable to achieve the target nozzle flow during ASC actuation. Figure 3.12 illustrates that the Sprayer-2 control system had a slow response when increasing the pump speed to meet the target system flow rate. Slow system response was observed when 2, 3 or 4 boom-sections were simultaneously turned OFF. The overall off-rate error and ST, for nozzles remaining ON, was up to -23.1% and 54.6 s respectively (Table 3.2). It was interesting to note that nozzle off-rate was only 0.7% when four boom-sections were turned OFF, but this was achieved after 54.6 s of nozzle flow rate instability. Therefore, under-application would have occurred until all the sections were turned ON and the system stabilized around the target rate which required 0.3 to 5.1 s. These static results corresponded with the observed response under field conditions at example Locations 1 and 3.

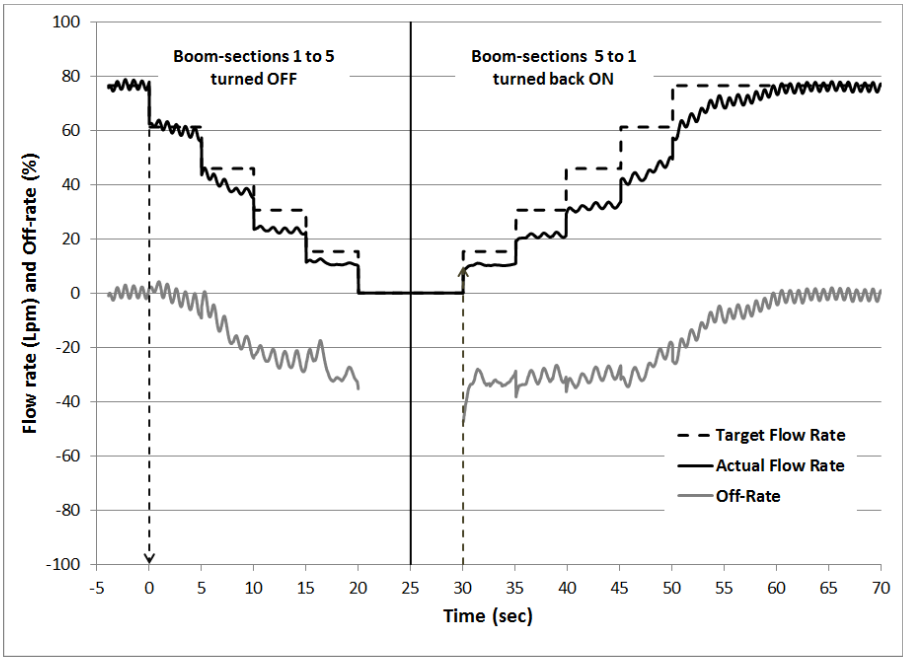


Figure 3.12. Overall mean nozzle flow rate and off-rate error for Sprayer-2 when turning boom-section valves sequentially OFF and ON at 5-second intervals. The sprayer was set to spray at 93.5 L/ha application rate and 16.1 kph forward speed.

Table 3.2. Mean nozzle off-rate and settling time (ST) when turning boom-sections OFF and then back ON at 24.1 kph forward speed and 140.2 L/ha application rate for Sprayer-2.

	----------- Sections OFF -----------		----- All sections back ON ---	
Booms OFF	Off-Rate Error (%)	ST5 (s)	Off-Rate Error (%)	ST5 (s)
1 & 2	-11.7	0.6	0.6	0.3
1, 2 & 3	-23.1	17.5	1.2	2.3
1, 2, 3 & 4	0.7	54.6	1.2	5.1

Similar experiments at four target pressures using Sprayer-1 indicated the control system was able to maintain the nozzle flow rate within ±10.0% of the target when turning all boom sections OFF and ON (Figure 3.13). The average nozzle off-rate was +3.8% during this test; however momentary drop occurred when sections were turned ON. These spikes likely resulted from pressure and flow buildup in the system plumbing which was necessary to achieve the target rate and transpired quickly. Similar nozzle flow response and off-rate was observed for 138.0, 276.0 and 552.0 kPa. The static ASC actuation tests for Sprayer-1 and Sprayer-2 indicated that there were distinct differences in control system response and nozzle flow rate management between the two sprayers.

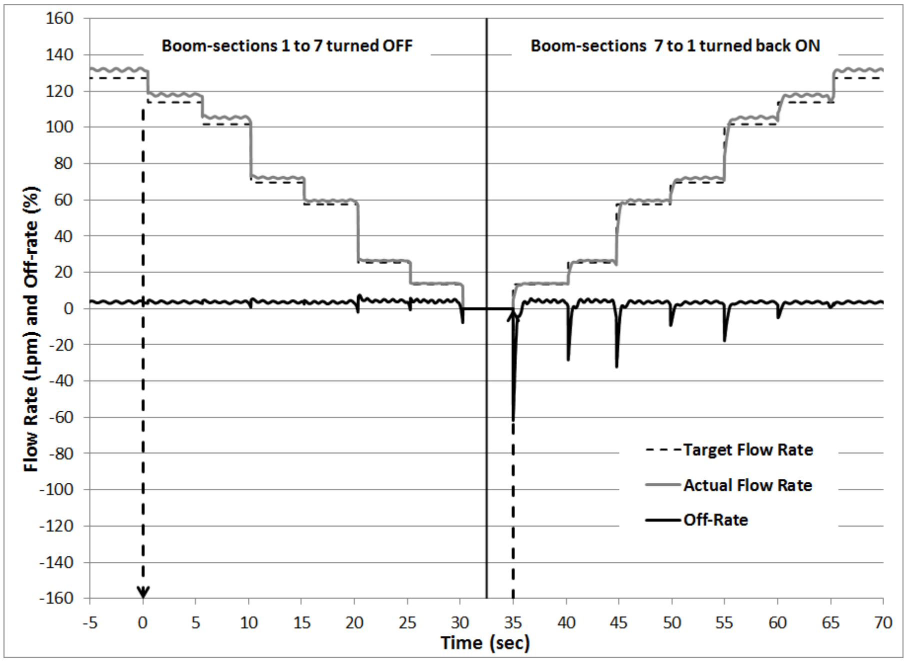


Figure 3.13. Overall mean nozzle flow and off-rate error for Sprayer-1 when turning boom-sections sequentially OFF and ON at 5-second intervals. For this static test, the target pressure was set at 414 kPa and ground speed at 19.3 kph equivalent to a 109.2 L/ha target rate or 128.6 Lpm system flow.

3.5 SUMMARY

Off-rate errors during field experiments were attributed to the control system's inability to maintain the target application rate during ASC actuation and ground speed variations. Results indicated that sprayer deceleration coupled with ASC actuation (sections OFF) contributed to over-application, while ASC actuation (sections ON) and sprayer acceleration resulted in under-application. Sprayer-2 static experiments reinforced field test results which found that under-application may occur more often than over-application from ASC actuation and ground speed changes. Static test results for Sprayer-2 demonstrated that over-application was associated with lower ground speeds (<16.1 kph) where nozzle flow stabilization required 15.0 to 20.0 s in some cases. Conversely, under-application was more likely to occur at ground speeds exceeding 16.1 kph along with ASC actuation for Sprayer-2. These results suggested a different control algorithm may be required to better maintain the target nozzle flow during ASC actuation and sprayer acceleration and deceleration. The control algorithm may be designed to look ahead at the final target rate and automatically select dynamic control algorithms based on sprayer acceleration, deceleration or ASC actuation or magnitude of required rate change. Static testing for Sprayer-1 indicated that the control system was able to maintain the target rate during ASC actuation. In general, static experiments suggested that control system response was fast and accurate for Sprayer-1. However, overall results suggested that nozzle off-rate errors can occur no matter the type of control technology implemented.

As the number of control sections increase (e.g. auto-nozzle for Sprayer-2), the control resolution (width of control) gets smaller thereby requiring a quicker control system response during ASC actuation and ground speed changes. While increasing the number of control sections can improve application accuracy the demand for improved control system response time is amplified. The inability of the control system to quickly respond during ASC therefore can result in off-rate errors. Sprayer field performance can therefore vary depending upon the feedback response mechanism selected plus algorithms used by rate control systems. The results of this study suggest that a tradeoff exists between control resolution and current controller response capabilities. Operators seeking to minimize the impact of nozzle pressure or flow variations should be aware of this tradeoff.

Minimizing system flow adjustments required for ASC actuation or ground speed changes can help address some of the issues reported in this study. Operator skill and behavior contribute to sprayer acceleration, deceleration and ASC actuation required during field operations. Field shape and size may affect how an operator chooses to traverse a field while spraying. Therefore, operators should be educated to understand current sprayer control technology to help enhance system efficiency.

Finally, the similarity between static and field tests suggested that static tests can provide a reasonable understanding of sprayer performance during field operation. While control systems have reduced overall misapplication, caution should be exercised when increasing control system demands. In the end, overall product efficacy must be preserved. Comparative field tests on sprayers with different control systems should be conducted to better understand potential application errors to improve system design and setup.

3.6 CONCLUSION

The following conclusions were drawn from this study:

- Nozzle CVs were greater than 10% for a short duration when each of the auto-boom (0.5 s) and auto-nozzle (0.2 s) sections were turned ON, while CVs were normally below 10% during stable operating conditions. The difference in CV likely resulted from system compliance between the nozzle tip and flow control point, which was greater for the auto-boom system compared to auto-nozzle control.
- While CVs were calculated using only the ON sections, it was observed that nozzles in OFF sections continued to spray for up to 3.5 s for auto-boom and 0.2 s for auto-nozzle control systems.

- Nozzle off-rate errors were greater than ±10% for rectangular fields when exiting and reentering spray zones at the headland. Off-rate errors occurred when operating at angled approaches and departures to no-spray zones (i.e. grassed waterways and other obstacles) within irregular shaped fields. Field results indicated that nozzle off-rate error was associated with ASC actuation along with acceleration and deceleration of the sprayer. ASC actuation contributed more to under-application whereas acceleration and deceleration contributed to both under- and over-application.
- For the auto-nozzle control system, ground speeds less than 16.1 kph and ASC actuation resulted in unexpectedly high nozzle flow settling times (>20 s) during static tests. These results indicated that long settling times can contribute to nozzle off-rate thereby impacting overall application accuracy.
- Static tests provided similar results to field testing. Therefore, static tests can provide realistic understanding of in-field sprayer performance, reducing field testing time.

CHAPTER 4

REAL-TIME PRESSURE AND FLOW DYNAMICS DUE TO BOOM-SECTION AND INDIVIDUAL NOZZLE CONTROL ON AGRICULTURAL SPRAYERS

4.1 ABSTRACT

Most modern spray controllers when coupled with a differential global positioning system (DGPS) receiver can provide automatic section or swath (boom-section or nozzle) control capabilities which minimize overlap and application in undesirable areas. This technology can improve application accuracy of pesticides and fertilizers, thereby reducing the overall amount of applied inputs while enhancing environmental stewardship. However, the system response on sprayer boom dynamics from turning boom sections manually ON and OFF or using ASC technology has not been investigated. Therefore, a study was conducted to develop a methodology and subsequently perform experiments to evaluate tip pressure and system flow variations on a typical agricultural sprayer equipped with a controller that provided both boom-section and nozzle-section control. To quantify flow dynamics during boom- or nozzle-section control, a testing protocol was established that included 3 simulation patterns under both flow compensation and no-compensation modes achieved through the spray controller. Overall system flow rate and nozzle tip pressure, at 10 locations along the boom, were recorded and analyzed to quantify pressure and flow variations. Results indicated that the test methodology generated sufficient data to analyze nozzle tip pressure and system flow rate changes. The tip pressure for the compensated section control tests varied between 6.7% and 20.0%, which equated to an increase of 3.7% to 10.6% in tip flow rate. The pressure stabilization time when turning boom- and nozzle-sections OFF, was 25.2 s but approached 15.6 s when turning these section back ON for the flow compensating tests. Though it took extended periods for the tip pressure to stabilize, the system flow rate typically stabilized in less than 7 seconds. The tip flow rate was consistently higher (up to 10.6%)

than the target flow rate indicating the system flow did not truly represent tip flow during section control. The no-compensation tests exhibited tip pressure increases up to 35.7% during boom- and nozzle-control which equated to an 18.2% increase in tip flow. Therefore, flow compensation had better control of tip flow rate as compared to results for the no-compensation tests. A consistent difference existed in dynamic pressure response between boom-section and nozzle-section control. Increased tip pressure and delayed pressure stabilization times indicated that application variability can occur when manually turning sections ON and OFF or implementing ASC technology but further testing is needed to better understand the effect on application accuracy in agricultural sprayers.

4.2 INTRODUCTION

Pesticide and nutrient transport via runoff or leaching from agricultural land to surrounding surface and ground water bodies poses a potential environmental and public health concern. In 2006, US farmers spent $8.8 billion on pesticide application (ERS-USDA, 2008). With the environment becoming an increasingly sensitive issue, on-farm pesticide and nutrient application needs to be performed accurately to ensure only the amount prescribed is applied where needed. However, over- and under-application can commonly occur when applying these crop inputs. Further, calibration and proper maintenance can impact the performance of sprayers. Grisso et al. (1989) conducted a field survey of 103 private herbicide applicators in Nebraska and reported that only 30% were applying herbicide within 5% of the intended application rate. Based on these results, they estimated an additional cost of $3.11/ha due to over-application of herbicides equating to a $4.26 million loss for the state of Nebraska. Sprayer application errors are typically due to worn nozzle tips, inaccurate calibration or inability to maintain required flow rate in the system during spraying (Grisso et al. 1989; Hofman and Solseng, 2004). Equipment operators can also impact the application performance by deviating from the desired swath, causing double- to no-coverage in areas. Overlap generally occurs at headland turns, when operating within point rows, and between adjacent passes.

Today, most large self-propelled sprayers control application rate base on required system flow. The controller uses a flow meter for closed loop control then either controls an in-line valve or pump speed to maintain the set target rate in the controller regardless of ground speed changes or width changes (turning boom sections ON or OFF). Thereby, this closed loop approached minimizes application errors by adjusting the system flow to meet the required target rate. Al-Gaadi and Ayers (1994) reported that a spray controller reduced application errors to within -7% to 1% compared to a ground driven system which produced a larger range of errors between -18% and 5%. Ayers et al. (1990) reported that a Dickey-John SC 1000 pressure based sprayer control system maintained an application error of less than 5% with ground speeds varying from 3.2 to 9.7 km/h.

Over the past couple of decades, rate controllers have also evolved to implement variable rate application (VRA) of inputs such as nutrients and pesticides. Past research on the response and accuracy of rate controllers has been conducted on variable-rate technology (VRT). Prior experiments on VRT have shown that real-time response of the controller was influenced by the type of rate controller, control hardware selection and ground speeds (Ayers et al., 1990). The response time includes time delays between when the control signal was conveyed to and when the application rate was actually attained (Fulton et al., 2005a). Rockwell and Ayers (1996) designed and constructed a variable-rate direct nozzle injection field sprayer and concluded that the system took 3.8 s to go from 10% to 90% of the step input. The reaction time for the control system in response to the differential global positioning system (DGPS) receiver can be as high as 2.2 s while maintaining a horizontal accuracy of 1 m (Al-Gaadi and Ayers, 1999). Another study indicated that application errors for direct injection systems were estimated to be as high as 40% for mistreated areas of the field with the chemical rate change at the nozzles occurring as much as 80-m past the desired step change location (Qiu et al., 1998). Another issue when using direct injection systems is how product introduced into the spray plumbing, upstream of the nozzles and boom valves, gets delivered across the boom. Lateral location of nozzles along the boom also affected the application accuracy of boom injection sprayers (Miller and Smith, 1992). However, Vogel et al. (2005) indicated that rate changes for a variable-rate sprayer usually consisted of a smooth increase or decrease in herbicide rates, except application rate spikes occurred when transitioning from OFF (areas requiring no input) to back ON. The use of “fast” control valve produced flow rate spikes that reached as high as 450 L/ha between old and new target rates. A sprayer with a control system can provide accurate application rates within 2.3% of the desired rate but could have lag times ranging from 15 to 55 s (Anglund and Ayers, 2003).

More recently, a precision agriculture (PA) technology called automatic section control or ASC turns ON and OFF sections or individual control mechanisms, like boom valves, nozzle solenoids, planting row clutches, etc., to reduce the over-application of crop inputs. ASC technology was initially implemented on sprayers to enhance the application of liquid pesticides, fungicides and nutrients. This technology utilizes a global positioning system (GPS) or Global Navigation Satellite System (GNSS) receiver along with application software to record areas which have already been sprayed or have been mapped as no-spray regions. If the boom-section or nozzle starts to apply in these areas, the spray controller will respond by turning the boom-sections or nozzles OFF accordingly. The use of ASC technology can potentially result in 15.2% to 17.5% reduction in sprayed area by way of efficiently managing boom sections (Luck et al., 2010).Therefore, overlap at headlands and within point rows is reduced thereby providing product savings.

Rate control systems inherently have response time delays which can be classified into two types; 1) control system response and lag time and 2) dynamic stabilization time due to spray system configuration (Fulton et al., 2005b). Intermittently shutting nozzles ON and OFF on one side could increase operating pressure on the other side of the sprayer (Salyani, 1999). Though the concerns regarding control system response have been reported by many researchers, boom dynamics, which may cause off-target application, have not been reported for sprayers equipped with ASC. The fundamental understanding of boom dynamics is important to understand in order to develop 1) control systems and new technology and 2) the associated mechanical design (e.g. boom plumbing and related hardware) of agricultural sprayers. This understanding becomes even more pertinent as the size of agricultural sprayer increases and as we try to reduce the control aspect down to individual nozzle. Real-time pressure differences during automatic boom-section/nozzle control needs to be investigated to understand their impact on application efficacy. Therefore, the objectives of this study were to 1) evaluate real-time system flow rate and tip pressure variations across the boom for a typical agricultural sprayer using various boom-section and nozzle control tests, and 2) compare and contrast flow dynamics for a controller providing feedback flow compensation to no-compensation during boom-section and nozzle control tests.

4.3 MATERIALS AND METHODS

4.3.1 SPRAYER AND DATA AQUISITION SYSTEM

All experiments were conducted using a three-point hitch mounted 18.3 m agricultural sprayer (Schaben Industries, Columbus, NE, USA). The sprayer boom was divided into three sections: (1) left, (2) center and (3) right. There were a total of 37 nozzles spaced at 50.8 cm across the boom. Boom sections 1 and 3 were 6.1-m wide having 12 nozzles each, while section 2 had 13 nozzles and was 6.6 m wide. The sprayer was plumbed using a 2.54-cm inner diameter (ID) hose from the boom valves to each of the 3 boom sections. A 1.91-cm ID hose was used to connect nozzle bodies along each boom section. The length of the hose from the boom valve manifold to each boom section was 7.62 m for sections 1 and 3 but 2.44-m for section 2. Teejet 11003 extended range flat spray tips were selected as nozzles. Each nozzle was equipped with a 12 VDC solenoid valve (Capstan Ag Systems, Inc., Topeka, Kansas, USA) to turn individual nozzles ON/OFF. The sprayer used a hydraulically driven centrifugal pump (FMC-150-HYD-206, ACE Pumps Corp., Memphis, TN, USA). A commercially available spray controller was used for all tests. This system used a turbine-type flow meter (Model No. RFM-60P, Raven Ind., Sioux Falls, SD, USA) and 2.54-cm butterfly type control valve (Model No. 063-0171-120, Raven Ind., Sioux Falls, SD, USA) to regulate the overall system flow rate. The calibration numbers used for the control valve, and flow meter were 2123 and 700, respectively as suggested by manufacturer's literature. For the control valve number of 2123, the first digit (2) represents the valve backlash digit which controls the time of the first correction pulse after detecting a change in correction direction of the valve. Backlash values can range from 1 (short pulse) to 9 (long pulse). The second digit (1) controlled the response time of the control valve motor with a range of 0 (fast response) to 9 (slow response). The third digit (2) was the valve brake point digit or point where the control valve would start to turn at a slower rate to avoid any overshoot when adjusting to the target rate. The values of the break point ranged from 0 to 9, where 0 corresponded to 5%, 1 to 10% 2 to 20% and on up to 9 for 90% of the target rate. The fourth digit (3) represents the dead band which sets the allowable difference between the target rate and the actual application rate. For the control valve used, the dead band can be set between 1 and 9 with 1 representing an allowable 1% difference and 9 corresponding to an allowable 9%. The flow meter calibration number indicated 70 pulses per 37.85 liters. The rate control system provided flow compensation (C) when programmed to the automatic control mode and no-compensation (NC) in the manual mode. During the compensation tests, the controller attempted to maintain the set target rate (L/ha) with any changes in application width (nozzles or boom-section turned ON and OFF) and/or ground speed. The rate controller was set to simulate a 56.8 L/min flow rate at a ground speed of 9.7 km/h.

To measure nozzle tip pressure (Figure 4.1), thin film pressure transducers (Model No. 1502 B81 EZ 100 PSI G, PCB Piezotronics Inc., Depew, NY, USA) were used at 10 nozzle locations. Nozzles were numbered starting from the left side between 1 and 37 with transducers mounted on nozzles 1, 8 12, 17, 20, 22, 25, 29, 35 and 37 (Figure 4.2). The pressure transducers had a measurement range of 0 to 689.5 kPa with reported accuracy of ≤ 0.25% full scale and a response time of ≤ 1 ms. Another pressure transducer was mounted at the boom valve manifold to monitor the overall system pressure at the same location where the analog pressure sensor providing feedback to the operator was plumbed by the sprayer manufacturer. Input signal to boom valves was used to decide the ON and OFF status of boom valves based on high (13 VDC) and low (0 VDC) voltage of the boom valves. The analog signals from pressure transducers and the three boom valves were sampled using two National Instrument (NI) 9221 analog input modules. System flow rate was measured using the existing inline flow meter connected to a Measurement Computing^{TM} (MC) USB-4303 counter/timer board. A program in LabVIEW version 8.6 was written to read the analog signals, and frequency from the MC board. The developed LabVIEW program also converted the analog signal from the various transducers to a pressure and the flow meter frequency to the system flow rate. All data was time stamped and written at 50 Hz to a *.TXT file for analyses.

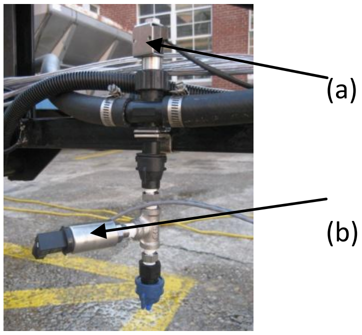


Figure 4.1. Illustration of nozzle body setup equipped with a Capstan solenoid body (a) and pressure transducer (b).

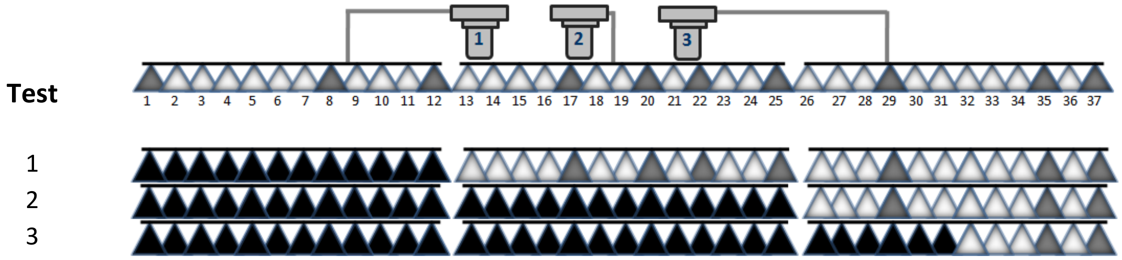


Figure 4.2. Sprayer plumbing configuration from the 3 boom valves to each boom-section; number assignment between 1 and 37 from left to right for each nozzle. Gray triangles represents nozzles equipped with pressure transducers while black triangles indicate nozzles turned OFF for the various tests.

4.3.2 EXPERIMENTAL DESIGN

A total of 10 tests were conducted and replicated three times to evaluate real-time system flow and tip pressure (Figure 4.2). The testing procedure was comprised of 2 boom-section (B) and 3 nozzle control (N) tests. During each test, boom/nozzle-sections with stable system pressure were turned OFF and then switched back ON allowing system pressure to stabilize each time between OFF and ON. For each test, the sprayer was allowed to run for 60 s to attain stable system pressure before turning boom/nozzle-sections OFF (Figure 4.3). The locations for installing ten pressure transducers were established with the intent to record pressure changes at varying distances from the point of liquid entry at each boom section. During the two boom control tests (1 and 2), either one or two consecutive boom sections were turned OFF then back ON, respectively. The first two nozzle control tests (1 and 2) consisted of 12 and 25 nozzles, respectively, turned OFF and then back ON which emulated the tests in which boom-sections 1 or 2 were turned OFF and then back ON. The only difference being the point of control (boom valves versus nozzles) for comparative reasons. The third nozzle control test (3) consisted of turning 31 nozzles OFF then back ON to evaluate conditions when only a few nozzles remained ON. The boom- and nozzle-section tests represent unique operating conditions when using ASC technology. The real-time tip pressure will directly reflect the extent to which the control system was successful in maintaining constant application rates during ASC engagement and disengagement. These tests will also quantify the stabilization time for tip pressure and system flow rate during these engagements and disengagements, thus providing insight on control system response time and boom plumbing dynamics. Comparison of flow compensation and no-compensation tests will ascertain the controller’s ability to regulate and maintain system flow rate for the set target rate.

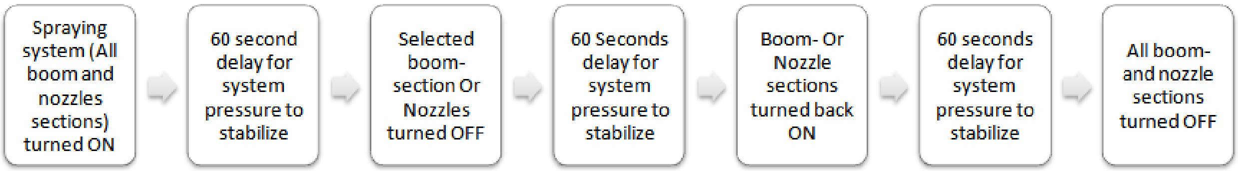


Figure 4.3. Data collection procedure used for all tests.

Test and data collection procedures for boom- and nozzle control tests were kept the same (Figure 4.3) for all tests. The data was collected for 2 boom-section control tests with compensation (B1-C and B2-C), 2 boom-section tests with no-compensation (B1-NC and B2-NC), three nozzle control tests with compensation (N1-C through N3-C) and 3 nozzle control tests with no-compensation (N1-NC through N3-NC). The data for all 10 tests were analyzed separately for the part of the experiment when sections were turned OFF and subsequently back ON.

A program in MATLAB was written to compute the initial nozzle pressure before initiating a test, final settling pressure (FP), settling time (ST), percent overshoot (OS), lag time, boom valve input signal, or OFF/ON, time, flow rate stabilization time, and pressure stabilization time. Boom valve input signal of 13 VDC was considered ON and OFF otherwise. The flow meter calibration number corresponds to the number of pulses for every 37.8 liters of fluid passing through the flow meter; therefore system flow rate was calculated using the following equation:

$$FR = \frac{10 * f * 3.24}{MCN}$$ **(Equation 4.1)**

Where

FR = system flow rate (L min^{-1})

MCN = meter calibration number for flow meter

3.24 = a constant to convert gallons per second to L min^{-1}

f = flow meter frequency (Hz)

The settling time represented the difference between times of observation of +/- 5% change in tip pressure changed from the initial system pressure to the time when tip pressure finally reached and stayed within +/- 5% of final pressure after the boom-section(s) was turned OFF. In the data table the average values of final pressure, percent change in pressure, pressure settling and stabilization times considering only the ON boom-section(s)/nozzles have been presented. In addition to pressure and system flow rate, boom input signal to each boom valve was recorded to estimate pressure and flow rate stabilization times. *Pressure stabilization time* (PST) was defined as the difference between the time the input signal actuated a boom valve to the time when the pressure settled and remained within 5% of the final value. The lag time was computed by taking the time difference between when the first nozzle on the section observed a pressure change compared to when the other nine nozzles observed an initial pressure change. Therefore, the PST is the sum of the settling and lag time. The *flow rate stabilization time* (FST) represented the difference between the time when the boom valve shuts OFF to the time when the system flow rate settled and remained within 5% of the final value. For presentation purposes, only one pressure sensor from each of the boom-sections was selected and presented along with the system flow rate. A black dotted line was used to separate when boom valves or nozzles were shut OFF (left side of line) and when they were turned back ON (right side of line).

An analysis of variance (ANOVA) was conducted in Statistical Analysis System software (SAS Institute, Inc. NC, USA) using the General Linear Model (GLM) procedure to ascertain if statistical differences existed between tip pressure, PST and FST based on the mean values of these parameters during different tests. Means and standard deviations for different parameters were also calculated using the GLM procedure. A two sample t-test was used to obtain statistical differences between initial and final tip pressures for each test. Multiple comparisons of tip pressures for all tests were conducted using the Tukey-Kramer procedure. The tip pressure coefficient of variation (CV) was computed across the boom which signified the tip spray uniformity for any point in time. All statistical analyses were conducted using a 95% confidence interval. A second order polynomial regression line ($\boldsymbol{y = -2 * 10^{-5}\, x^2 + 0.0059x + 0.1003}$, r^2 = 0.999) was fitted to the manufacturers tip pressure versus flow rate data to estimate tip flow rate (Teejet, 2008).

4.4 RESULTS AND DISCUSSION

4.4.1 FLOW COMPENSATION TESTS

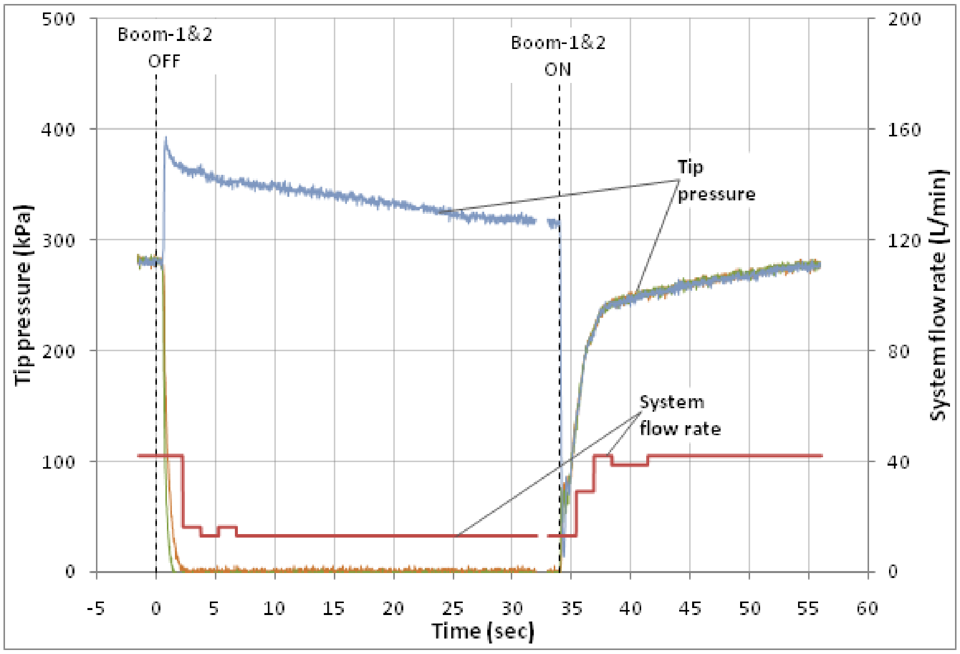
The increase in tip pressure ranged from 6.7% to 20% during flow compensated tests Table 4.1) when turning boom or nozzle-section(s) OFF. Boom control tests (B1-C and B2-C) demonstrated tip pressure increases between 9.4% and 14.1 % while tip pressure increases between 6.7% and 20.0% were observed during nozzle control tests (N1-C, N2-C and N3-C). The highest tip pressure increase (20.0%) occurred during N3-C test when 31 out of 37 nozzles were turned OFF. The increase in nozzle tip pressure from 6.7% to 20.0% during various tests was equivalent to 3.7% to 10.6% increase in the tip flow rate. Figure 4.4a and Figure 4.4b depict the nozzle tip pressure variation during B2-C and N2-C tests, respectively. It can be determined from Figure 4.4 that once sections 1and 2 were turned OFF, the final tip pressure could not stabilize to the initial pressure conditions even for the flow compensation tests. This increase in tip pressure could be due to the fact that the controller adjusted the system flow rate based on feedback from the flow meter and did not take into account the tip pressure or boom flow dynamics when sections were turned OFF. Controller response based only on flow rate feedback also resulted in second order dampening and delayed stabilization of tip pressure during section control. This result illustrated in Figure 4.4 where the tip response does not correspond to the upstream flow meter response, providing feedback to the controller may be important to consider for control systems or when designing the mechanical aspects for sprayers (e.g. plumbing, valve locations, fittings, etc.).

This consideration would minimize application errors when these conditions are encountered under field operation. However, additional research is required to more fully understand the responses measured, determine the primary cause, and how to reduce this effect in order to minimize potential application errors.

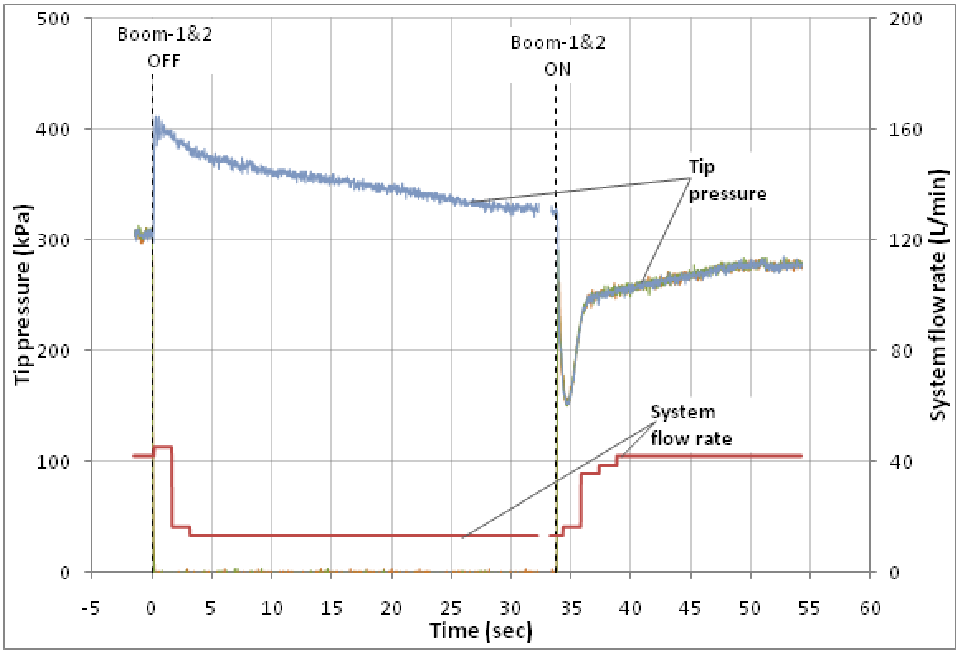
Table 4.1. Summary of tip pressure and flow rate results (means presented with standard deviation provided in parenthesis) for both flow compensation and no-compensation when sections were turned OFF[1].

Test	IP (kPa)	% Change in tip pressure	% increase in tip flow rate	OS (%)	ST (s)	FST (s)	PST (s)
Compensation							
B1-C	278.7	9.4^{ef}	5.1	6.5^{d}	0.3	2.9^{ab}	1.0^{d}
	(0.1)	(0.1)	(0.0)	(0.3)	(0.1)	(0.6)	(0.1)
N1-C	296.2	6.7^{f}	3.7	12.3^{c}	11.3	4.7a	11.4^{c}
	(0.4)	(1.0)	(0.5)	(0.7)	(1.6)	(2.4)	(1.1)
B2-C	277.5	14.1^{cde}	7.3	23.0^{a}	23.7	3.9^{ab}	24.4^{a}
	(0.1)	(0.9)	(0.5)	(1.5)	(3.3)	(0.8)	(3.3)
N2-C	294.0	11.^{8efd}	6.3	25.1^{a}	25.1	3.5^{ab}	25.2^{a}
	(1.6)	(4.7)	(2.7)	(2.9)	(2.2)	(0.3)	(2.2)
N3-C	304.9	20.0^{b}	10.6	19.1^{b}	17.9	2.7^{b}	18.0^{b}
	(1.1)	(2.4)	(1.2)	(1.0)	(1.5)	(0.0)	(1.5)
No-Compensation							
B1-NC	285.9	17.2^{bc}	9.3	1.7^{e}	0.1	2.5^{ab}	0.7^{d}
	(0.1)	(0.2)	(0.1)	(0.2)	(0.0)	(0.2)	(0.0)
N1-NC	293.0	16.0^{bcd}	8.8	3.4^{ed}	0.1	1.9^{b}	0.1^{d}
	(0.4)	(0.6)	(0.4)	(0.3)	(0.0)	(0.4)	(0.0)
B2-NC	284.9	35.3^{a}	18.1	4.0^{ed}	0.1	3.0^{ab}	0.7^{d}
	(0.2)	(0.6)	(0.3)	(0.9)	(0.0)	(0.7)	(0.0)
N2-NC	292.3	34.1^{a}	17.8	3.7^{ed}	0.1	4.3^{ab}	0.1^{d}
	(0.4)	(1.5)	(0.7)	(0.4)	(0.0)	(0.2)	(0.0)
N3-NC	301.3	35.7^{a}	18.2	6.1^{d}	0.2	2.4^{ab}	0.3^{d}
	(0.3)	(0.9)	(0.4)	(0.8)	(0.0)	(0.4)	(0.0)

[1] IP=initial pressure; OS=overshoot; ST=settling time; FST=flow stabilization time; and PST=pressure stabilization time. Within columns, means with same letter (superscript) are not statistically different at the 95% confidence level. The values within parenthesis indicate standard deviation.



(a)



(b)

Figure 4.4. Tip pressure, system flow rate and input signal to boom valves 1 and 2 for flow compensation tests B2-C (a) and N2-C (b).

Table 4.2. Summary of tip pressure and flow rate results (means presented with standard deviation provided in parenthesis) for both flow compensation and no-compensation when sections were turned back ON[1].

Test	US (%)	ST (s)	FST (s)	PST (s)	FP (kPa)
Compensation					
B1-C	-52.5^{d}	10.7	4.8^{ab}	10.9^{b}	275.1
	(0.0)	(0.2)	(4.6)	(0.2)	(0.3)
N1-C	-9.2^{f}	3.0	3.0^{b}	3.0^{c}	278.6
	(0.2)	(0.4)	(0.8)	(0.4)	(0.3)
B2-C	-99.3^{a}	15.3	6.4^{ab}	15.6^{a}	277.2
	(0.0)	(1.6)	(4.5)	(1.5)	(0.1)
N2-C	-46.4^{e}	11.8	5.9^{ab}	14.0^{ab}	278.6
	(0.0)	(0.6)	(2.0)	(3.4)	(0.1)
N3-C	-59.7^{c}	14.4	10.7^{a}	14.4^{a}	276.5
	(0.0)	(0.8)	(1.3)	(0.8)	(0.0)
No-Compensation					
B1-NC	-42.8^{e}	1.6	3.1^{b}	0.9^{c}	284.1
	(0.0)	(1.7)	(2.1)	(0.1)	(0.1)
N1-NC	-4.1^{g}	0.2	3.0^{b}	0.2^{c}	289.6
	(0.0)	(0.0)	(1.6)	(0.0)	(0.2)
B2-NC	-71.4^{b}	1.0	4.7^{ab}	1.2^{c}	285.5
	(0.0)	(0.1)	(1.2)	(0.1)	(0.1)
N2-NC	-3.5^{g}	0.2	4.0^{b}	0.3^{c}	291.7
	(0.0)	(0.0)	(1.1)	(0.0)	(0.1)
N3-NC	-3.8^{g}	0.2	2.3^{b}	0.2^{c}	297.9
	(0.2)	(0.1)	(0.3)	(0.0)	(0.1)

[1] US=undershoot; ST=settling time; FST=flow stabilization time; PST=pressure stabilization time; and FP=final pressure. Within columns, means followed by same letter (superscripts) are not statistically different at the 95% confidence level. The values within parenthesis indicate standard deviation.

System response was found to be different while shutting boom-sections OFF (Table 1) versus turning them back ON (Table 4.2). The boom system pressure stabilization took longer time than expected during compensated section control tests. The PST varied between 1.0 and 25.2 s (Table 4.1) when turning sections OFF and between 3.0 to 15.6 s after a section(s) was turned back ON (Table 4.2). The tip pressure exhibited a second order under-dampened response, with gradual decrease in tip pressure before stabilization, when the boom-section(s) was shut OFF (Figure 4.4a); whereas, the tip pressure gradually increased and exhibited a second order over-dampened system when turning sections back ON (Figure 4.4b). Tip pressure stabilization times for the B2-C and N2-C tests were 24.4 and 25.2 s, respectively when sections were turned OFF while it was 15.6 and 11.9 s, respectively when turning sections back ON. A similar trend can be seen between the B1-C and N1-C tests involving one boom-section. The flow meter and flow control valve response time largely contributes towards the PST. The higher PSTs when turning the sections OFF could be due to the slow response of the flow control valve while adjusting the system flow to the target rate. During nozzle control, the liquid within the hoses between the boom valves and nozzles remain pressurized. Therefore when the sections were turned back ON, nozzle control demonstrated lower pressure stabilization times as compared to the boom-section tests.

The percentage overshoot in tip pressure for the flow compensation tests varied from 6.5% to 25.1% (Table 4.1) which was proportional to the pressure settling times (0.3 to 25.1 s) with the exception of B1-C. The tip pressure demonstrated 46.4% to 99.3% undershoot when the sections were turned back ON. The lower undershoot and PST during nozzle control tests signified that nozzle control provided lower tip pressure variations across the boom and faster pressure stabilization when turning sections back ON. There was little difference between the settling and pressure stabilization times, demonstrating negligible lag time for all flow compensation tests. Therefore, a 3.7% to 10.6% increase in final tip flow rate with a pressure stabilization time between 1.0 and 25.2 s can result in off-target application when boom-sections or nozzles are turned OFF. The over-damped system response accompanied by PSTs between 3.0 and 15.6 s when turning boom-sections back ON will essentially contribute to under-application even when implementing flow compensation.

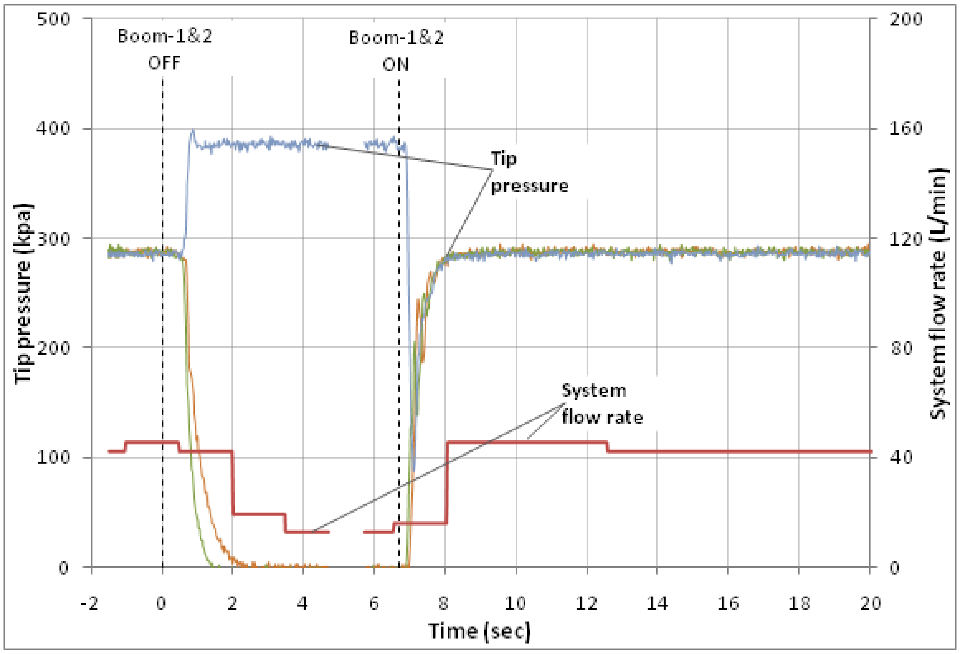
For the boom-section tests, the PST within the boom-sections turned OFF was up to 1.6 s. This delay in tip pressure reaching zero could be attributed to the fact that the nozzles continued to spray for a short time until the residual pressure in the boom-section equaled the pressure drop across the nozzles. During both boom-section and nozzle control tests, the tip pressure responded almost instantaneously (< 260 ms) and coincided with the input signal (dotted black line; Figure 4.4a) to boom-valve or nozzle solenoids while shutting OFF or ON.

The system flow rate stabilized between 2.7 and 4.7 s (Table 4.1) when boom-sections were turned OFF. Flow rate stabilization took between 3.0 and 10.7 s (Table 4.2) when turning boom-sections back ON. The FST was longer when a section(s) was turned back ON compared to turning them OFF. It was also observed that the system flow rate was sensitive to the number of boom-sections initially turned OFF before turning the entire boom back ON. Of interest, these results did not indicate any trend between the flow rate stabilization times and the number of boom-sections or the percentage of the boom turned OFF. The longer flow stabilization time for B2-C compared to B1-C was expected since B2-C required a larger adjustment by the control valve. It was also interesting to note that the system flow rate stabilized to the target rate value within 7.0 s while the tip PST lasted as long as 25.1 s with tip pressures remaining 20% more than the initial pressure. The sample standard deviation between the replications for tip pressure, percent change tip flow rate, OS, FST and PST was found to be low except for the FST when turning sections back ON (Table 4.1 and Table 4.2). Thus, these results suggested that the system flow does not directly correspond to the tip flow rate response during these stabilization periods. The difference in the PST and FST also implied the need for a secondary, real-time feedback mechanism to provide information to the spray controller to manage boom dynamics. This feedback mechanism could use both tip pressure and system flow rate as a means to either implement a look-ahead time to make adjustments in a timely manner or adjust settings to minimize application errors.

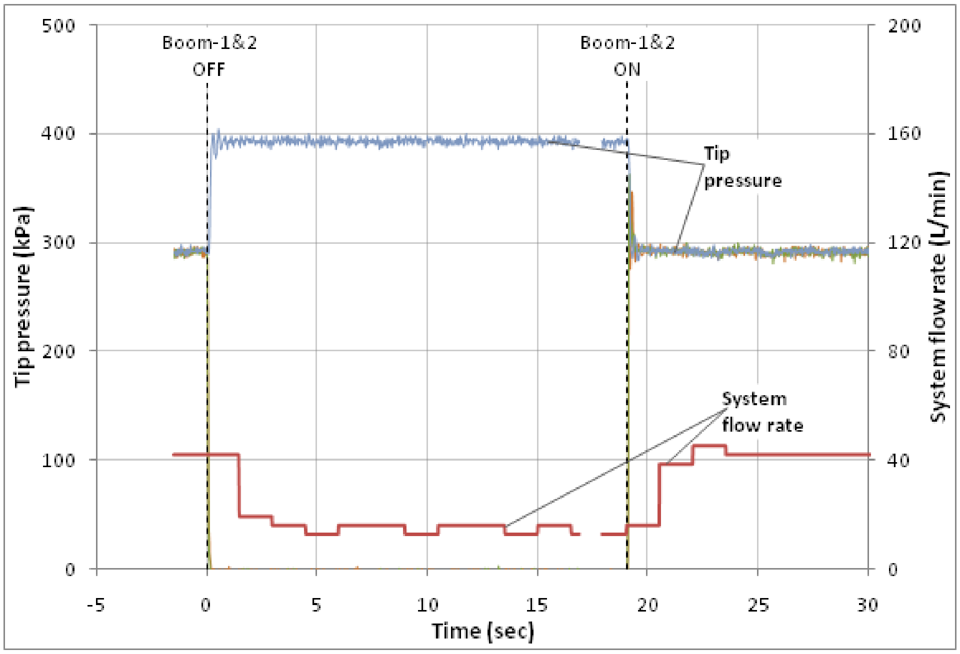
4.4.2 NO-COMPENSATION TESTS

The no-compensation tests demonstrated tip pressure increases between 16.0% and 35.7% (Table 4.1) when boom-sections were turned OFF. This range equated to a respective increase of 8.8% to 18.2% in tip flow rate. There was a two fold increase in tip pressure for B2-NC (two boom-sections OFF) compared to B1-NC test (one boom-section turned OFF). The trends for the increase in tip pressure were also similar to the compensating tests. Tip pressure for no-compensation tests increased by two times as compared to the compensated tests. The final tip pressure after the sections were turned back ON stabilized close to the initial conditions (Table 4.2).

The PST was less than 1.2 s for all no-compensation tests whether turning boom-sections OFF or ON (Figure 4.5). System response when shutting boom-sections OFF versus turning them back ON was similar to the compensating tests. Overshoot in tip pressure for the no-compensating tests was between 1.7% and 6.1%, lower than compared to the compensating tests (6.1% to 25.1%). The system FST varied between 2.0 to 6.9 seconds and was comparable to the flow compensated tests when boom-sections were turned OFF. Similar trends in PST and FST were observed when boom-sections were turned back ON. The system flow rate deviated by 24.6% (B2-NC) and tip flow rate increased up to 18.2% during no-compensation tests. It is expected that no-compensation would have resulted in redistribution of energy in the hoses thereby increasing the tip flow rate during different tests. This redistribution of energy and increased tip flow rate could be the predominant reason for near equal system flow rate even during no-compensation tests. The unit frequency on the flow meter represented 3.2 L/min with a response time of 1.5 s, therefore a flow meter with better resolution and faster response will help further understand system flow rate behavior. Tip pressure response during no-compensation boom-section and nozzle control tests was similar to that during compensation tests. The computed standard deviations were considered small for all the no-compensation data (Table 4.1 and Table 4.2).



(a)



(b)

Figure 4.5. Tip pressure, system flow rate and control input signal for tests B2-NC (a) and N2-NC (b).

Faster response during no-compensation tests should not be interpreted as an advantage over no-compensation when using ASC technology. The quick response during no-compensation is due to the rapid redistribution of energy in the hoses to those nozzles still ON since the controller has no feedback from the flow meter. Therefore, flow compensation is a tradeoff between having tip pressure increases between 6.7% and 20% with some settling time to achieve the target system flow rate as opposed to a 35.7% increase during the N3-NC test.

The tip pressure increase was greater during boom control tests and was roughly proportional to the percentage or number of boom-section(s) or nozzles turned OFF (Figure 4.6). This tip pressure increase could be result of net decrease in pressure drop across control system hardware but needed further investigation. Tip pressure increase resulted in statistically different and proportional increase in tip flow rate, which can result in increase in application errors, as the number of sections turned OFF increases. The unequal increase in tip pressure during comparative boom and nozzle control tests could be largely due to the location point of shutting the liquid ON/OFF. For a given system flow, there will be dissimilar pressure drop across boom valve(s) and nozzle(s), which might be the cause of different effective tip pressures during boom-section(s) and nozzle control tests. The final nozzle tip pressure when the boom/nozzle section(s) were turned back ON stabilized close to the initial tip pressure (Table 4.2).

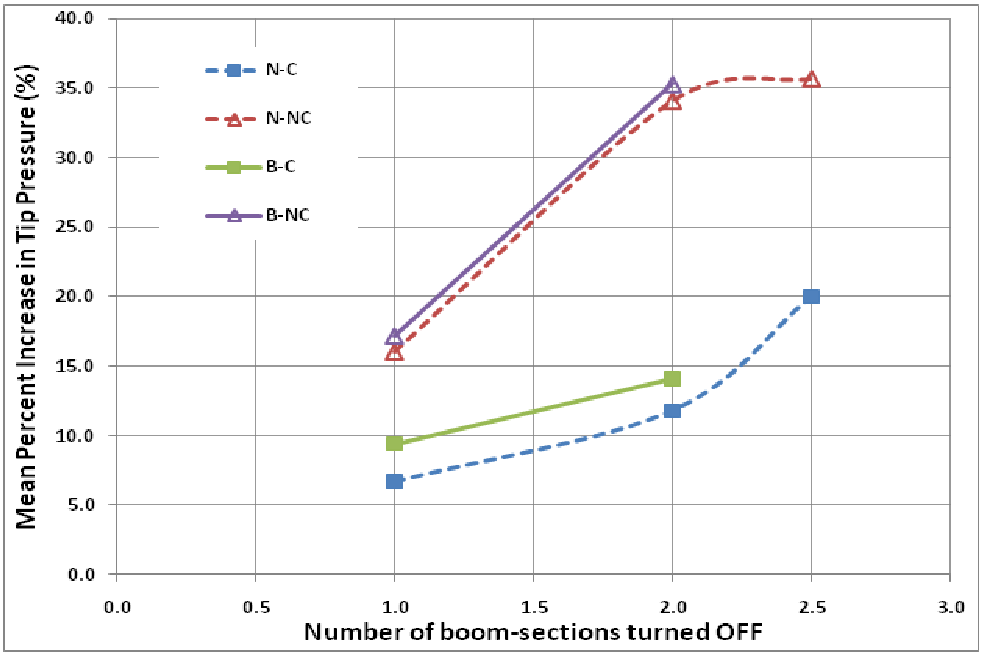


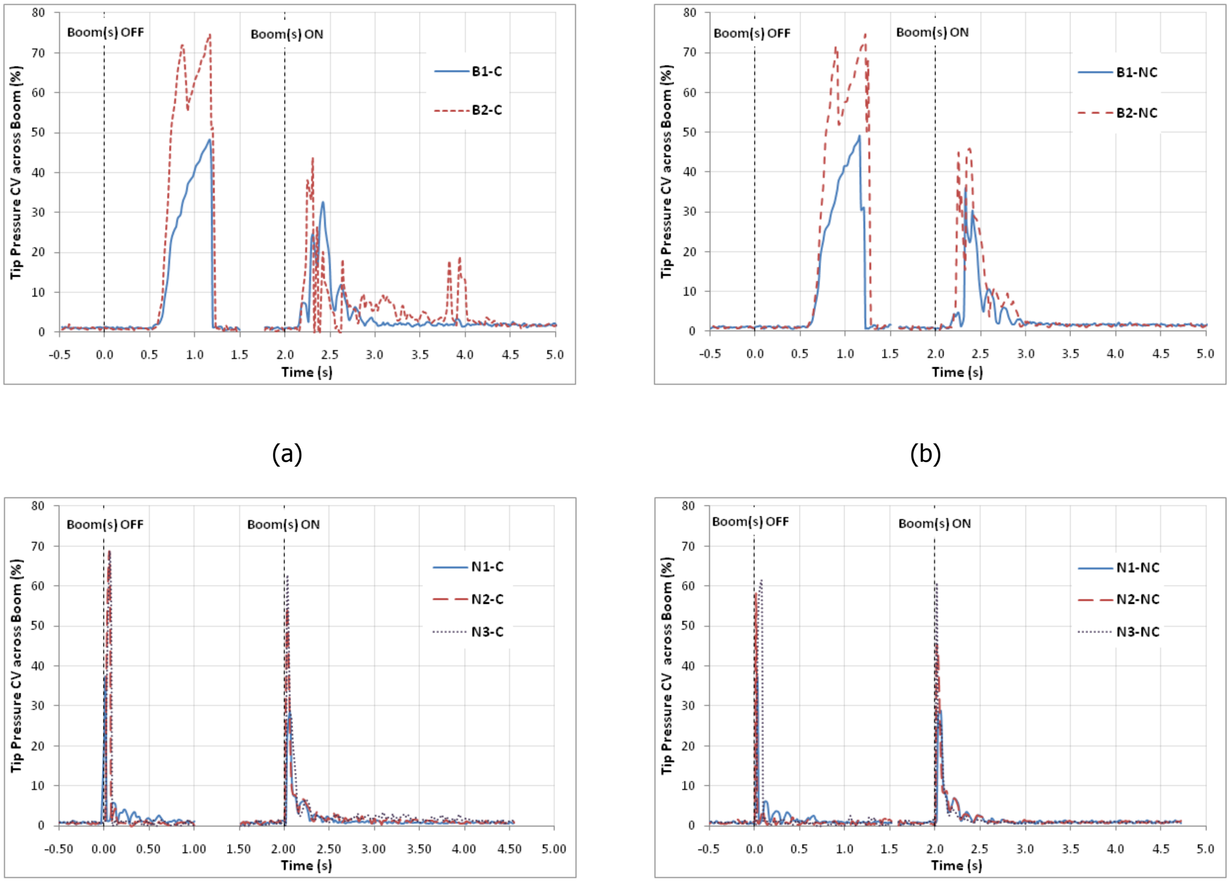
Figure 4.6. Mean percent increase in tip pressure for those nozzles which remain ON versus the number of boom-sections turned OFF for the various tests.

The ANOVA procedure demonstrated that mean tip pressure during all the boom- and nozzle-control tests were significantly different from the initial and final tip pressures (Table 4.3). The PST with sections turned OFF and; PST and FST after sections were turned back ON, were also significantly for different tests. Multiple comparisons of all tests using the Tukey-Kramer indicated that PSTs when turning sections ON/OFF and FST when turning sections back ON was significantly different for flow compensation; whereas the PSTs and FSTs were not significantly different for no-compensation boom- and nozzle control tests.

Table 4.3. ANOVA results for mean tip pressure, PST and FST during different section control tests.

Source	Degrees of Freedom	Sum of Squares	P-value
Tip pressure-Sections turned OFF	9	901.0	<.0001
PST-Sections turned OFF	9	2978.1	<.0001
FST-Sections turned OFF	9	21.41	0.0155
PST-Sections back ON	9	1221.3	<.0001
FST-Sections back ON	9	169.8	0.0095

The tip pressure (Figure 4.7) along the boom had a CV of up to 70% for a short duration (< 600 ms) during PST whereas it was less than 1.5% otherwise. The boom control tests had tip pressure CVs over 7% for approximately 1.8s (Figure 4.7a and Figure 4.7b) when turning sections back ON. In general, nozzle control offered faster tip pressure response when turning sections ON/OFF thereby resulting in lower CVs. The results also indicated that the magnitude in tip pressure increase depended upon the number of boom-sections or nozzles turned OFF (Figure 4.6). The control point for turning ON/OFF boom valves or nozzle solenoids impacted boom system flow dynamics. Nevertheless, ASC generated complex and unique flow dynamics affecting tip pressure and system flow rate. Considerations on how to improve the PST beyond 10 seconds is needed to minimize application errors. However, further testing, both lab and field is needed to fully understand flow dynamics while using automatic section control technology. The tip pressure and PST between turning sections ON and OFF was consistently different for the various tests which indicated a need to reassess rate controller strategies during ON and OFF routines. The comparison between compensation and no-compensation showed that although ASC technology did control pressure and flow rate, but could not maintain constant tip pressure/flow rate to match application rate during section control. In general, pressure stabilization times and elevated tip pressures during and after system flow rate stabilization suggested that off-target application errors can occur when using automatic section control technology. The tests selected for the purpose of evaluating boom fluid dynamics provided a preliminary understanding of the control system behavior when turning boom-sections or nozzle solenoids ON and OFF.



(a)

(b)

(c)

(d)

Figure 4.7. Tip pressure CVs across the spray boom during the boom-section, flow compensation (a) and no-compensation (b) tests along with the nozzle, flow compensation (c) and no-compensation (d) tests.

4.5 CONCLUSIONS

The following conclusions were drawn from this study:

- Tip pressure varied between 6.7% and 20.0% from the initial tip pressure which was equivalent to an increase of 3.7% to 10.6% in tip flow rate during flow compensation tests. The tip pressure increase was approximately proportional to the percentage of boom-sections turned OFF during all boom-section and nozzle control tests.
- The tip PST, when turning sections OFF and back ON, was up to 25.2 and 15.6 seconds, respectively for the compensating tests. Conversely, the system FST was typically less than 7

seconds during compensated and no-compensated section control tests. Therefore, these results highlighted that a difference can exist between the control measurement point (flow meter) and actual point of application, the nozzle, when using ASC technology. However, additional research is needed to better understand this difference but one does exist.

- Nozzle control tests showed an almost instant response (< 140 ms) in tip pressure, demonstrating negligible lag time. The point of control (boom valve versus nozzle) contributes significantly towards boom flow dynamics during section control.
- Nozzle tip flow rate was always higher (4% to 11%) than the flow rate measured by the flow meter. Therefore, system flow rate did not represent tip flow rate during section control.
- Flow compensated boom- and nozzle control tests exhibited 20.0% increase in tip pressure though managed system flow rate to match target application rate. The no-compensation tests demonstrated up to 24.6% variation in system flow rate and 35.7% increase in tip pressure during boom- and nozzle control tests.

CHAPTER 5

REAL-TIME NOZZLE FLOW UNIFORMITY WHEN USING AUTOMATIC SECTION CONTROL ON AGRICULTURAL SPRAYERS

5.1 ABSTRACT

Automatic section control (ASC) has been readily adopted by US producers on sprayers because it can improve in-field equipment efficiency and decrease overlap or input usage leading to economic savings while reducing environmental impacts. However there is limited knowledge about nozzle flow rate management when shutting ON/OFF of boom-sections or nozzles and possible impact on application accuracy. Therefore, an investigation was conducted to evaluate control system response in managing real-time nozzle off-rate and flow uniformity across the boom, for a typical agricultural sprayer using ASC. An 18.3-m sprayer was outfitted with commercially available individual nozzle and boom-section control. Tests were conducted to simulate sprayer moving OUT of point row into no-spray zone and then coming back INTO spray zone by selecting two point row scenarios having 20° and 70° angles were conducted at a 43.2 l/min application rate and 9.7 km/h ground speed. Ten high frequency response pressure sensors were randomly mounted across the boom to measure nozzle pressure. The nozzle pressures were converted to nozzle flow rate to calculate nozzle flow rate delay time, settling time, percent off-rate (percent difference between actual and target nozzle flow rate) and percent nozzle flow rate co-efficient of variation (CV), considering only ON boom-sections. Auto-boom scenarios were conducted with and with-out flow compensation while auto-nozzle scenarios were conducted without flow compensation. Results indicated that nozzle flow rate settling time varied from 0.4 to 14.4 s and nozzle off-rate between -2.4% and +28.7 for 70° point row auto-boom tests when moving OUT and back INTO point row. The machine moving OUT of point row resulted in over-application whereas moving back INTO point row resulted in under-application during flow compensated tests, thus demonstrating

different response for moving OUT/INTO point row. Nozzle flow rate CVs were more than +50% for a short duration (< 1.0 s) when reentering point rows, during all tests. Compensation tests for 20° point row tests highlighted the constraint of the control system to respond to certain situation where feedback response times can match up with the time at which the new targets were set forth for the controller. Overall results indicated that control system response time can impact nozzle off-rate and therefore controller should have an option to selectively actuate ASC only when the next target is manageable within control system response time limitations in order to minimize off-rate/target application.

5.2 INTRODUCTION

Pesticides and nutrients are inevitably required for efficient and economic production of crops. Rising input prices and $11.5 billion annual spending on agrochemicals in 2009 (USDA, 2010) coupled with ever increasing pressure on pesticide and fertilizer users to minimize off-rate application has motivated stakeholders to improve spray equipment to enhance application accuracy. Crop yield and quality depends greatly on the right amount of pesticides application across the field (Ozkan, 1987). Over-application can result in increased production costs along with potential damage to crops and the environment whereas under-application can lead to ineffective pest control potentially generating yield loss.

The development of rate control systems has improved the application accuracy of farm inputs. Rate controllers for sprayers are commonly classified as pressure or flow rate based control systems. Pressure based control systems usually provide the required flow rate by adjusting the system pressure depending upon the nozzle orifice size whereas flow based systems uses flow meter feedback to ensure accurate application. Most sprayer controllers used on self-propelled sprayers today are flow control based systems. The rate controller globally monitors and adjusts application rates based on real-time vehicle speed and application width while the operator concentrates on supervising the overall job. The user interface offers the operator flexibility to monitor and change application control options on-the-go. Dickey-John SC 1000 pressure based sprayer control system tested by Ayers et al. (1990) was able to maintain an error of less than 5% with ground speeds varying from 3.2 to 9.7 km/h. Al-Gaadi and Ayers (1994) found that the use of a spray rate controller compared to a ground driven system reduced application errors from -18% and 5% down to -7% and 1%. Rockwell and Ayers (1996) designed and constructed a variable-rate direct nozzle injection field sprayer and concluded that the system took 3.8 s to go from 10% to 90% of the step input. Intermittent switching between ON and OFF of nozzles on one side of the sprayer could increase the operating pressure on the other side (Salyani, 1999) potentially resulting in application errors attributed to pressure and flow rate differences. Vogel et al. (2005) evaluated a variable-rate sprayer and found that rate changes usually consisted of a smooth increase or decrease in herbicide rates, except an application rate spike occurred in situations when the prescribed rate changed from OFF to ON. The use of a fast control valve produced flow rate spikes that reached as high as 450 L/ha between the old (OFF) and new (300 L/ha) target rates.

The use of automatic section control (ASC) technology in Alabama has helped reduce over-application of pesticides and fertilizers by 1% to 12% per pass across fields (Troesch et al., 2010), in addition to improving environmental stewardship by impeding the proliferation on non-target zones including vegetative filter strips and grassed waterways. ASC technology closes the boom/nozzle solenoid valves whenever the sprayer covers an area that has already been sprayed or for no spray zones in point rows (Figure 5.1). Rate controllers use global positioning system (GPS) to determine spatial location and control the intended flow to each boom- or nozzle-section. Therefore, the grower never applies more than once already sprayed field areas, eliminating overlap, improving efficiency, save on time and farm inputs, and preserve fragile natural resources. The use of ASC technology potentially results in a 15.2%

to 17.5% reduction in sprayed area by way of efficiently managing boom sections (Luck et al., 2010a). Growers can potentially reduce the over-application area from 12.4% to 6.2% by using ASC instead of manually controlling the boom-section ON/OFF (Luck et al. 2010b). For all these positive benefits, ASC is slowly becoming a part of the package for sprayer control systems because of the ease of usage and farmers recognition of tangible benefits, particularly with savings.

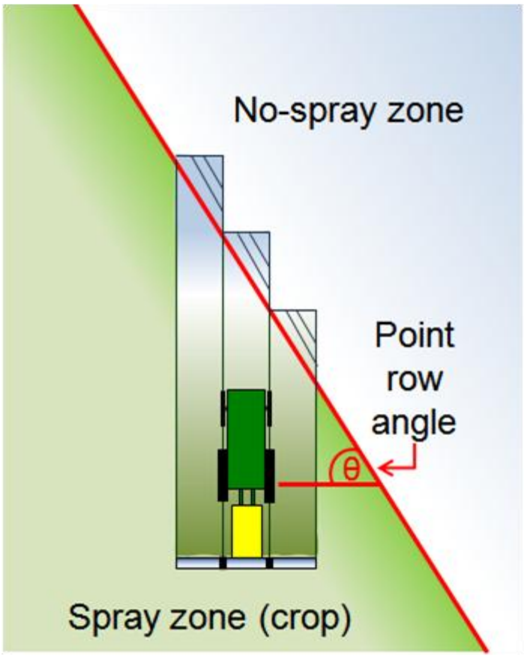


Figure 5.1: Illustration of ASC for a three-section sprayer boom moving from a spray zone into no spray zone at an angle. This example represents sprayer operation in point rows.

Effective spatial application using ASC depends on the ability of the rate controller to accurately control system flow rate thereby maintaining correct application rates during ASC actuation. The ON/OFF action requires a prompt reaction time between hardware components to maintain application efficiency. However, application controllers do have inherent limitations on speed of response. Application errors for direct injection systems can be as high as 40% for mistreated areas of the field and at times chemical concentration at the remote nozzles may change after as much as 80 m of travel past the desired step change location of the input command to the controller (Qiu et al., 1998). The lag times for a rate control system to provide accurate application rates within specified limits of the desired rate can range from 15 to 55 s (Anglund and Ayers, 2003). The reaction time for the control system in response to the DGPS receiver can be as high as 2.2 s while maintaining horizontal accuracy of 1 m (Al-Gaadi and Ayers, 1999). Apart from the control systems and GPS time delays, Grisso et al. (1989) and Miller and Smith (1992), reported that lateral location of nozzles along the boom can also impact the magnitude and temporal occurrence of application rate errors. These studies have highlighted that response time delays and application errors are inherently associated with using rate control systems and are often times governed by the hardware control algorithm capabilities to manage system response.

The full potential of precision agriculture (PA) technologies can only be attained when operated precisely (Mowitz, 2003). On today's farms, environmental concerns exist about over- application of pesticides and fertilizers which could increase the risk of environmental impacts such as runoff into water bodies near fields. Though many attempts have been made to report hardware time lags, no research has documented dynamic nozzle flow stability when implementing ASC. Therefore, the objectives of this study were to 1) evaluate the effect of point row angle on flow response across the boom and nozzle off-rate when using ASC, and 2) compare and contrast nozzle flow rate response during auto-boom and auto-nozzle control.

5.3 MATERIALS AND METHODS

This study was conducted in the Biosystems Engineering Department at Auburn University using a three-point hitch mounted 18.3-m sprayer (Schaben Industries, Columbus, NE USA). The sprayer was unfolded and operated in a static position for all tests using water. A John Deere 6420 tractor (Deere and Company, Moline, IL USA) was used as the source of hydraulic power for the sprayer; centrifugal pump (Model number FMC-150-HYD-206, ACE Pumps Corp., Memphis, TN USA).

The sprayer plumbing was a dry boom setup (Figure 5.2) consisting of three boom sections: left (1), middle (2) and right (3). The boom plumbing consisted of 37 nozzles on 0.51-m spacing. Boom sections 1 and 3 were 6.1-m wide having 12 nozzles each while boom section 2 was 6.6-m wide containing 13 nozzles (Figure 5.3). Hose sizes included using a 2.54-cm inner diameter (ID) between the boom valves to the T fitting on each of the 3 boom sections. Then, 1.91-cm ID hose was used to connect each nozzle body (Figure 5.3). The length of the hose from the boom valves to each boom section was 7.62 m for sections 1 and 3 and only 2.44 m for section 2. Teejet 11003 (Teejet Technologies, Wheaton, IL USA) extended range flat spray tips were used. Each nozzle body was equipped with a 12 VDC solenoid valve (Fig. 2; Capstan Ag Systems, Inc., Topeka, KS USA) to provide individual nozzle ON and OFF control. The sprayer was set to spray 140.5 L/ha ground speed of 9.7 km/h.

(a) (b)

Figure 5.2. Illustration of a) sprayer and data acquisition setup and, b) pressure sensors and solenoids mounted at nozzles along the boom-sections.

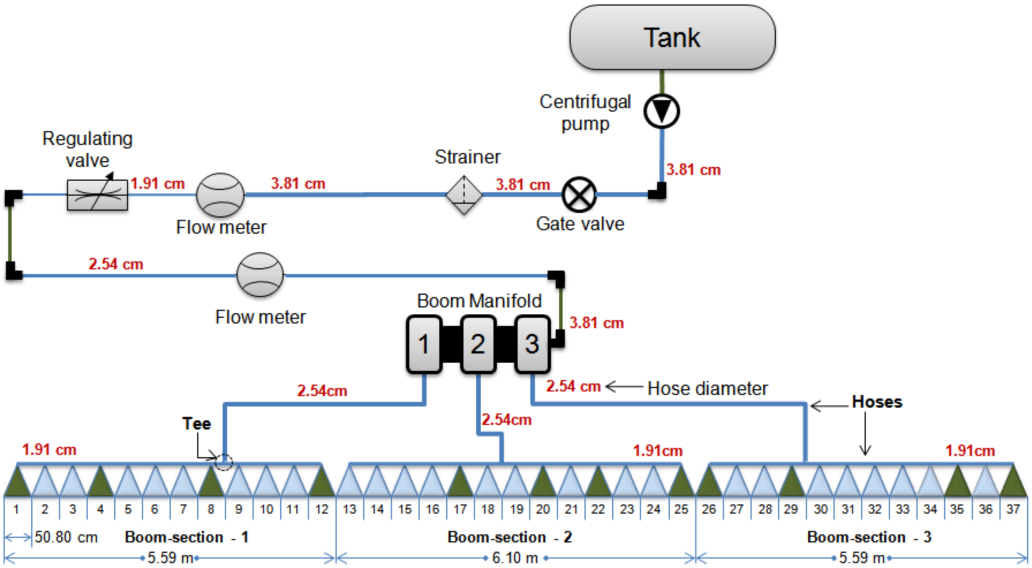


Figure 5.3. Sprayer plumbing configuration, illustrating flow control valve placement, boom valves, widths of boom-sections 1 through 3, nozzle spacing, hose sizes and nozzle distribution. Nozzles were numbered from left to right (ID between 1 and 37). Nozzles equipped with pressure sensors are shown in green.

A commercially available Raven Viper-II spray system controller was used. This system used a 3.81 cm poly turbine-type flow meter (Model RFM-15, Raven industries, Sioux Falls, SD USA) and 2.54-cm poly control valve (butterfly style) to regulate the overall system flow rate. The flow control valve calibration number (VCN) was set at 2123 within the spray controller for all tests, as recommended by the manufacturer. The four digits of the VCN (Table 5.1) are used to control the system response. Thereby, the 2123 VCN number set the controller to send relatively short pulse, relatively fast response to the valve thereby producing a 20% break point and 3% dead band.

Table 5.1. Flow control valve calibration number digits 1st through 4th controls the system response time of butterfly valve.

Digit	Control aspect	Range
1st	*Valve Backlash Digit* - controls the time of the first correction pulse after a change in correction direction is detected and has a range from.	Ranges from 1 to 9; where 1 represents short pulse and 9 long pulse
2nd	*Valve Speed Digit* - controls response time of control valve motor and can be set between	0 (slowest) to 9 (fastest).
3rd	*Brake Point Digit* - sets the percent away from target rate at which the control valve motor begins turning at a slower rate, so as not to overshoot the desired rate	Ranges from 0 to 9, where 0 = 5%, 1 = 10% and 9 = 90%
4th	*Dead-band digit* - dictates allowable difference between target and actual application rate, where rate correction is not performed.	Ranges from 1 to 9, where 1 = 1% and 9 = 9%.

The rate controller provided flow compensation when set to the automatic control mode and no-compensation in the manual mode. Nozzle pressure was measured with thin film pressure transducers (Model 1502 B81 EZ 100 PSI G; Figure 5.2a; PCB Piezotronics Inc., Depew, NY USA) and at a sampling frequency of 50-Hz. The pressure sensors were carefully located to measure nozzle pressure at different positions within boom-section. Another pressure sensor was mounted at the boom valve manifold to monitor overall system pressure. This sensor location coincided with the existing analog pressure gauge the operator views during operation. National Instruments CompactRIO™ cRIO-9014 controller, cRIO-9103 chassis, with a two NI 9221 C series analog modules were used to measure pressure and boom input signals. The overall system flow rate was measured using an inline flow meter connected to a NI 9403 C series digital input/output module. Two NI 9475 C series digital output modules on the same chassis were used to automatically switch ON or OFF the three boom valves or 37 nozzle solenoids. Relays or input/output modules (Model 70G-ODC15, Grayhill Inc., La Grange, IL, USA) were used as the intermediate control mechanism to turn either boom-sections or nozzle solenoid valves ON and OFF.

To evaluate real-time off-rate application and nozzle discharge uniformity (CV) across the boom using ASC during typical field scenarios, two point rows having 20° and 70° intersecting angles were selected for conducting the tests. Various irregular field boundaries from typical Alabama farms were studied in ArcGIS and typical highest (70°) and lowest (20°) point row angles were thus selected for point row tests. Auto-boom scenarios were conducted with controller flow compensation and no-compensation, while auto-nozzle scenarios were conducted with no-compensation. The rate controller was unable to be setup in the flow compensation mode for the auto-nozzle scenarios. The theoretical time required to close and open each boom-section/nozzle while spraying point rows was calculated based on ground speed (9.7 km/h) and boom/nozzle spacing (Figure 5.3). The resulting switching times for 20° and 70° point rows are presented in Table 5.2. Sections were turned OFF when the sprayer moved OUT of a point rows and back ON when the sprayer moved back INTO unsprayed point rows. LABVIEW-8.6 was utilized to develop program for automatically actuating boom or nozzle solenoid valves utilizing pre-determined times from Table 5.2. The test algorithm followed the sequence presented in Figure 5.4. Appropriate time delays were introduced to allow the system to stabilize as the sprayer exited and reentered point rows.

Table 5.2. Intended section OFF/ON control time and target flow rate to simulate 20° and 70° point row tests.

Point row angle	**Parameter**	**------------Boom-section------------**			**----Nozzle section----**
		1	**2**	**3**	**Single nozzle**
20°	ON/OFF Actuation time (sec)	0.83	0.90	0.83	0.07
	Target flow rate (L/min)	13.64	14.88	13.64	1.14
70°	ON/OFF Actuation time (sec)	6.25	6.77	6.25	0.52
	Target flow rate (L/min)	13.64	14.88	13.64	1.14

Figure 5.4. An example of field boundaries for Alabama, USA.

All tests (Table 5.3) were replicated three times totaling 18 tests. The boom and nozzle scenarios were selected to evaluate whether differences existed between auto-boom and auto-nozzle control. The main distinction between these scenarios is that flow is turned ON and OFF at individual nozzles versus at the boom valve typically located upstream of the nozzles (Figure 5.3). Each boom-control test data sets was divided into six parts: boom 1 OFF, booms 1 & 2 OFF, booms 1, 2 & 3 OFF, boom 1 ON, booms 1&2 ON and booms 1, 2 & 3 ON. All six scenarios were uniquely different from each other in a manner that during an experiment, different combination of boom sections was ON. The data sorted for these six scenarios involving auto-boom control (ABC) tests were analyzed separately. For auto-nozzle control (ANC) tests, the data involving exiting and, reentering point row was analyzed separately.

Table 5.3. Summary of test regimen for auto-boom control (ABC) and auto-nozzle control (ANC) for point row scenarios.

Application Rate (L/ha)	Ground speed (km/h)	Point row angle (°)	Section control	Controller setting
140.5	9.7	20	ABC	Compensation
				No-compensation
			ANC	No-compensation
		70	ABC	Compensation
				No-compensation
			ANC	No-compensation

The LabVIEW (LabVIEW , 2009) program logged pressure sensor and boom input signal data at 50 Hz along with a time stamp for data analyses. The nozzle pressures were converted to nozzle flow rates (Figure 5.5) using the manufacturer's stated pressure/flow relationship (Teejet, 2008). Target nozzle flow rate was computed using application rate, ground speed and number of sections ON. Number of boom-sections that are ON at any time during a test were determined by the measured control signal to each boom valve. Similarly MATLAB was used to log single nozzle actuation. Again MATLAB was used to calculate average values of initial nozzle flow rate (IFR), final nozzle flow rate (FR), average nozzle off-rate (OR), delay time (DT) and , settling time (ST) while Microsoft Excel was used to calculate coefficient of variation (CVs) for each nozzle (Table 5.4). Percent difference between actual and target nozzle flow rate was calculated to off-rate error. These tests were conducted under controlled conditions (stationary and level sprayer boom) and a ±3% dead-band. Nozzle flow rates beyond ±5% were considered off-rate. For settling time a ±2% band was selected because this value is typically used to understand control system response. Plots were generated to present how off-rate and CV varied when exiting and reentering point rows. The solid black line in the plots serves to visually separate the exiting (left side of line) from the reentering response (right side of line). Further, the dotted black lines are included as an indication of when booms or nozzles were turned ON or OFF.

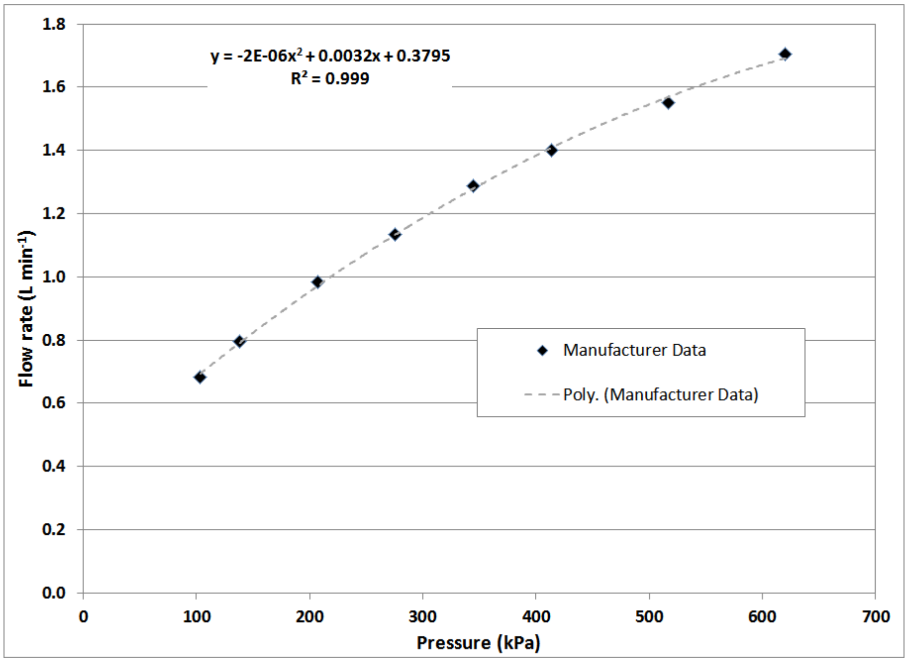


Figure 5.5. Spray tip flow rate versus pressure curve along with polynomial fit (Poly.) based on the manufacturers literature (Teejet, 2008).

Table 5.4. Nomenclature and definitions for various variables measured and computed.

Variable	Acronym	Definition
Initial flow rate	IFR	The average initial accumulated nozzle flow rate of three boom-sections before exiting or after reentering point rows.
Delay Time	DT	Represents difference between the time when the input signal to boom valve (s) and nozzle solenoids were sent and the time when ±2% change in the flow rate was observed considering only those sections which were ON at each time stamp.
Settling Time	ST	Difference between the time (seconds) when the nozzle flow rate was beyond ±2% after section(s) were turned OFF/ON and the time when nozzle flow rate settled and remained within ±2% of the final value.
Flow rate	FR	Mean overall system or accumulated nozzle flow rate considering all nozzles are ON when exiting and reentering point rows.
Off-rate	OR	Average final nozzle off-rate after the boom-section(s) exited or reentered point rows, considering only ON section(s) or nozzles.
Coefficient of Variation	CV	Represents nozzle flow uniformity across the boom when exiting and reentry to point rows. Calculated by taking mean and standard deviation of only those nozzle pressure values which were ON at each time stamp.

An ANOVA was conducted using the generalized linear model (GLM) procedure in SAS (SAS Institute Inc., 1999) analyzing nozzle settling time and off-rate . Multiple comparisons between tests were conducted using Tukey-Kramer procedure at 95% confidence interval to see if the differences exist between exiting and reentering point row with compensation and no-compensation.

5.4 RESULTS AND DISCUSSION

5.4.1 AUTO-BOOM 70° POINT ROW

Nozzle flow response during the ABC tests with flow compensation is presented in Figure 5.6. The nozzle flow rate had a delay time of 0.7 s, and settling time between 0.4 and 1.3 s (Table 5.5). The delay time and settling times in response to input signal to boom-section 1, while exiting 70° point row, is demonstrated in Figure 5.7. During reentry, the delay time ranged from 0.1 to 0.3 s and flow rate settled between 3.9 and 14.4 s (Table 6). The lag time during exit and reentry can be attributed largely to the time for the boom valve to close or open once the input signal was sent. This result was concluded since the nozzle flow in the OFF section(s) was equivalent to the rate in the ON sections when exiting and flow rate remained zero after the boom-section(s) reentered point rows, during this delay time. The difference in delay time when exiting and reentering might be attributed to dissimilar fluid momentum at the boom valves (closing versus opening) because theoretically, time to open or close boom valves was the same. The compliance of the hoses were not tested in this study, however the fluid momentum can also be impacted by variation in the energy within hoses. The flow rate settled rapidly when exiting but took up to 14 .4 s during reentering, which was expected since it takes time to build the nozzle pressure and thereby flow rate.

The nozzle off-rate was positive when exiting resulting in over-application, whereas sprayer reentry contributed to negative off-rate or under-application. It was expected that the controller flow compensation would maintain the nozzle off-rate within ±5%, since the controller was set at 3% dead-band. However, the resulting average off-rate during flow compensation tests was between +6.6% and

+10.7% (Table 5.5) when exiting point rows whereas, during sprayer reentry, the off-rate varied from -36.3% to -15.6% (Table 5.6). It is clear that though off-rate was more than ±5% of target nozzle rate during exiting, off-rate was within ±5% range only during reentry (Figure 5.6). The nozzle off-rate times indicated that over-application occurred for 6.1 to 6.2 s when exiting (Figure 5.6) but under-application lasted from 3.6 to 5.1 s during reentry (Figure 5.8). Nozzle flow uniformity (CV) was less than 1.0% at all times when exiting point rows. This result of low and unvarying CVs was expected. Conversely, nozzle flow uniformity did vary up to 50.0% (Figure 5.6) for a short duration during reentry but the mean CV was again less than 1.0%. The nozzle uniformity varied primarily when boom-sections 2 and 3 were turned back ON. A possible explanation for this finding was back pressure accompanied by complex dynamics in boom-section(s) occurring as a result of flow compensation and redistribution of fluid energy, thus generating pressure variations along the boom. Of interest, an under-damped response occurred when exiting point rows whereas reentry generated an over or critically damped response at the nozzles.

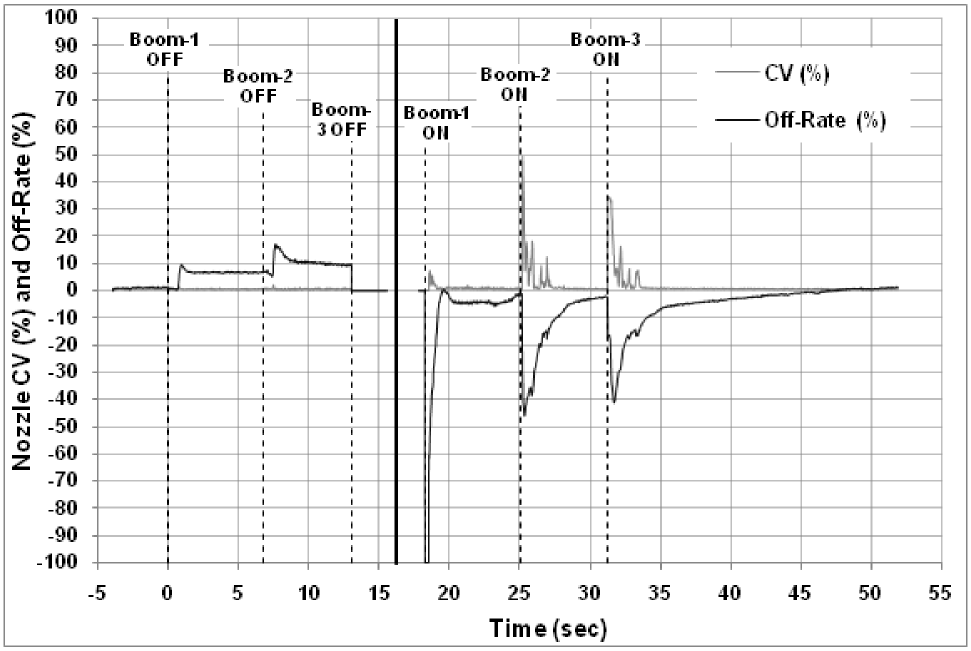


Figure 5.6. Nozzle CV and off-rate for a 70° point row ASC scenario with flow compensation.

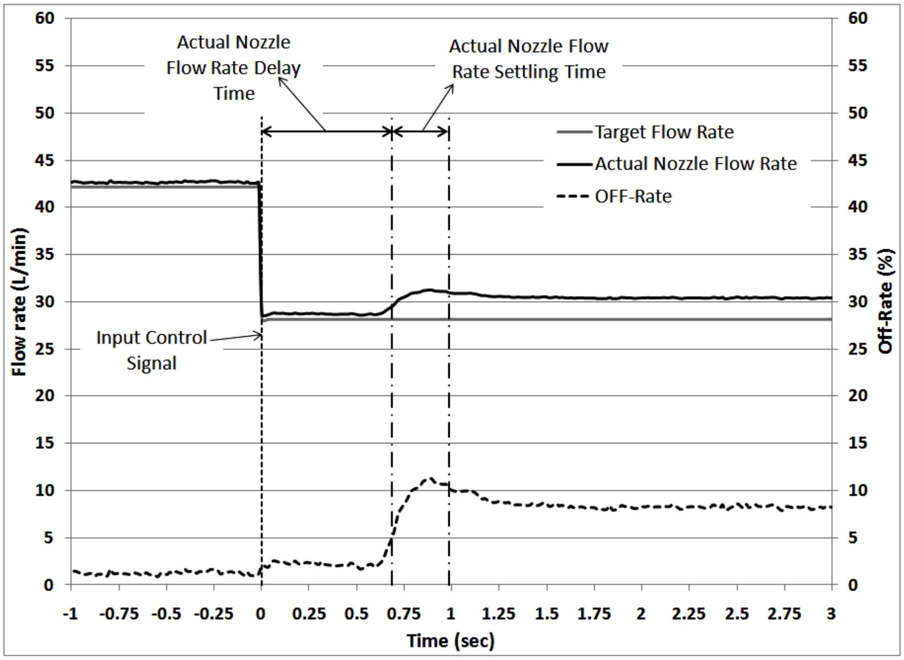


Figure 5.7. Nozzle flow rate delay (DT), settling time (ST), and off-rate (OR) response once 1 boom shut-off valve is turned off when exiting 70° point rows.

Table 5.5. Summary of nozzle flow rate delay time (DT), settling time (ST), final flow rate (FR), average nozzle off-rate (OR) and off-rate time (means presented with standard deviations in parenthesis) when exiting 70° point row during auto-boom tests with- and no (flow) compensation.

		Boom-section(s) Exiting							
Initial Condition		**----------- Section 1 -----------**				**----------- Section 2 -----------**			
FR (L/min)	**OR (%)**	**DT (s)**	**ST (s)**	**OR (%)**	**ORT (s)**	**DT (s)**	**ST (s)**	**OR (%)**	**ORT (s)**
Compensation									
42.5	0.9	0.7	0.4	6.6	6.1	0.7	1.3	10.7	6.2
(0.0)	(0.0)	(0.0)	(0.1)	(0.8)	(0.0)	(0.0)	(0.3)	(0.4)	(0.0)
No-compensation									
43.4	2.9	0.6	0.1	12.5	6.1	0.6	0.0	21.3	6.2
(0.1)	(0.1)	(0.0)	(0.0)	(0.1)	(0.1)	(0.0)	(0.0)	(0.1)	(0.0)

During the auto-boom no-compensation tests, the nozzle flow rate had delay time of 0.6 s when exiting and from 0.2 to 0.3 s while reentering (Table 5.6). The delay times with no-compensation were comparable to those with flow compensation, indicating response time delay of the hardware (boom valves). The flow rate settled almost instantly on exit whereas settling time varied from 0.2 to 2.0 s during reentry. The lower settling time was because of no-compensation but resulted in off-rate when exiting and during reentry. The off-rate or over-application during exiting (12.5% to 21.3%) and reentering of boom-sections 1 and 2 (8.6% to 14.7%) with no-compensation was apparently a result of increased flow and the boom-system being brought to equilibrium by virtue of maximum nozzle flow rate. These off-rate errors resulted in nozzle off-rate times from 6.1 to 6.2 s during exiting and 6.2 to 6.8 s when reentering point rows. When the 3rd boom-section reentered point rows, nozzle off-rate (-22.9%) occurred for 0.9 s before stabilizing within ±5%. The nozzle CVs were high for only a short duration for reentry especially once boom section 3 turned ON, but otherwise within 1.0% (Figure 5.8). The nozzle CV variations were similar to the flow compensation (Figure 5.6) but tended to be short lived for no-compensation (Figure 5.8) when boom-sections 2 and 3 were turned back ON. The off-rate in Figures. 6 and 8 are noticeably different suggesting quicker nozzle flow stabilization with no-compensation. However, no-compensation resulted in over-application for the entire period ASC was actuated. The only difference between compensation and no-compensation tests was the control valves ability to adjust to the target flow during the compensation tests. The off-rate and settling time observed during exiting and reentry for compensated tests could result from response time delays of flow control valve during ASC.

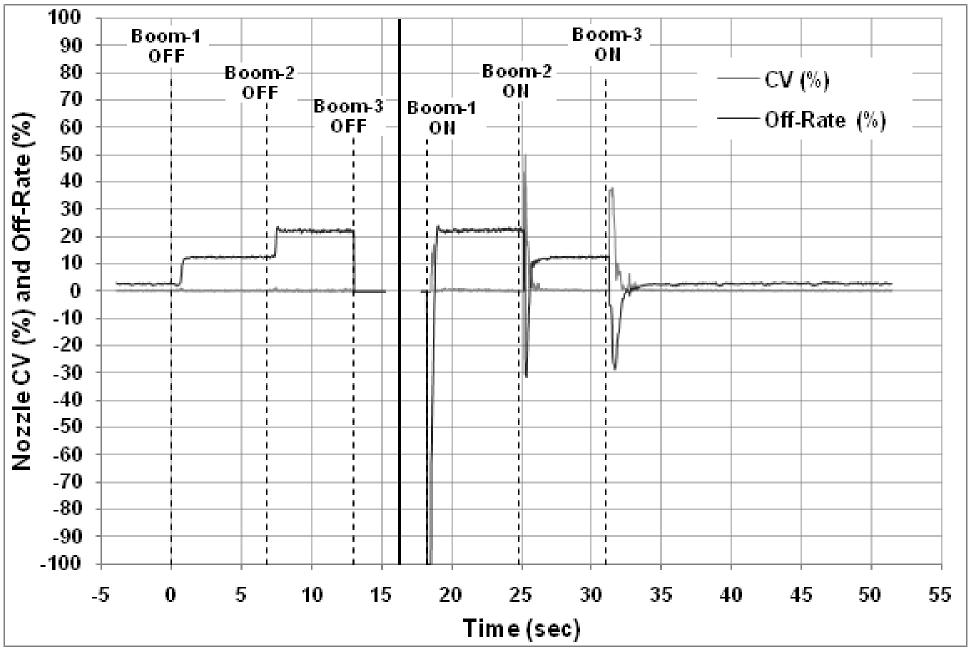


Figure 5.8. Nozzle CV and off-rate (OR) for a 70° point row ABC scenario with no-compensation.

Table 5.6. Summary of nozzle flow rate delay time, settling time, final off-rate and percent nozzle off-rate (means presented with standard deviations in parenthesis) when reentering 70° point row during auto-boom tests with- and no (flow) compensation.

Initial condition	Boom-section(s) Reentering											
	-----------Section 1-----------				-----------Section 2-----------				-----------Section 3-----------			
FR (L/min)	DT (s)	ST (s)	OR (%)	ORT (s)	DT (s)	ST (s)	OR (%)	ORT (s)	DT (s)	ST (s)	OR (%)	ORT (s)
Compensation												
0.0 (0.0)	0.3 (0.0)	4.6 (1.2)	-36.6 (0.2)	3.9 (1.1)	0.2 (0.0)	3.9 (0.2)	-20.9 (0.3)	3.6 (0.4)	0.1 (0.1)	14.4 (0.7)	-15.6 (0.3)	5.1 (0.3)
No-compensation												
0.0 (0.0)	0.3 (0.0)	0.4 (0.0)	14.7 (0.1)	6.8 (0.0)	0.2 (0.0)	0.7 (0.1)	8.6 (0.1)	6.2 (0.0)	0.2 (0.0)	2.0 (0.5)	-22.3 (0.2)	0.9 (0.0)

The results of the statistical analysis for 70° auto-boom tests with and no-compensation are presented in Table 5.7 and

Table 5.8. ANOVA results suggest that there is evidence that the means of the settling time, off-rate and off-rate time differ. The multiple comparisons suggested that settling time, off-rate and off-rate for the sprayer, with compensation, when exiting point rows was different than during reentry ($p \leq 0.0001$).

Also the mean settling time and off-rate for 70 compensation tests were significantly different from no-compensation tests, except for the off-rate when section 1 was turned OFF for exit and 3 was switched back ON at reentry (Table 5.7). It was expected that compensation and no-compensation tests for 70° point rows will have different nozzle off-rate, since the control valve was not compensating for flow rate. Though off-rate times were significantly different for reentry, overall off-rate time was roughly the same during both compensation and no-compensation. Finally, extended settling times indicated that for longitudinal (direction of travel) off-rate can occur during point row operation for a much higher period of time than expected. The flow control and feedback mechanism needs to be further studied to reduce off-rate errors when using automatic section control technology.

Table 5.7. ANOVA results for nozzle ST and OR during 70˚ auto-boom tests.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
ST	9	518.05	57.56	256.69	<.0001
Error (ST)	20	4.48	0.22		
OR	9	10592.32	1176.92	147.00	<.0001
Error (OR)	20	160.13	8.00		
ORT	9	90.55	10.06	73.82	<.0001
Error (OR)	20	2.73	0.13		

Table 5.8. Nozzle flow rate ST and OR multiple comparison from statistical analysis using Tukey-Kramer.

	-------------- Tukey Grouping* ---------------		
Tests	**ST**	**OR**	**ORT**
1Boom OFF-Compensation	D	B	AB
2Boom OFF-Compensation	C, D	B	A
1Boom OFF-No-compensation	D	B	AB
2Boom OFF-No-compensation	D	A	A
1Boom ON-Compensation	B	D	C
2Boom ON-Compensation	B	C	C

3Boom ON-Compensation	A	C	B
1Boom ON-No-compensation	D	AB	A
2Boom ON-No-compensation	C, D	B	A
3Boom ON-No-compensation	C	C	C

*Means with same letter are not significantly different ($p \geq 0.05$).

5.4.2 AUTO-BOOM 20° POINT ROW

For the 20° point row tests, the flow rate did not stabilize while exiting and reentering point rows during both compensation (Figure 5.9) and no-compensation (Figure 5.10), except when the 3rd boom-section reentered the point rows. There was a delay time of 0.7 s after boom-section 1 exited and 0.3 s as it reentered point rows. The nozzle flow rate settling time (13.6 s), when the 3rd section reentered 20° point rows was comparable to that for the 70° point rows (14.4 s). The 70° point row tests suggested the control system needed more than 1.0 s to respond and manage nozzle flow rate during ASC actuation when exiting, and several seconds while reentering. The time to shut OFF and ON boom-section was less than a second for all 20° tests (Table 5.2). Therefore, the 20° results indicated ASC actuation was too quick for the controller to promptly respond. The off-rate also remained beyond ±5% and only settled after 3rd section reentered point row. The nozzle CVs were less than 0.6% except when boom-section 2 and 3 reentered point row when the nozzle CVs were up to 30.0% for short duration. The comparison of flow compensation and no-compensation results (Figure 5.9 and Figure 5.10) indicated that feedback control did try to manage nozzle flow but the controller was getting a new target before it could make a change. Thus, in regards to flow rate, settling time and off-rate, it can be concluded that response during 20° point row ASC actuation will be comparable irrespective of whether flow compensation is used or not. For smaller point row angles where the rate controller does not have sufficient time to respond to ASC actuation, it will be prudent to look ahead and adjust to the final operating conditions when all sections are ON versus trying to provide real-time flow adjustment when section turns ON/OFF. These tests can be related to control system response on headland turning and suggests, realistically you can control nozzle flow only under certain operating conditions when using ASC. Therefore, to obtain the correct response for point row angles like 20° or less, a control feedback mechanism with a faster response time and higher resolution is required to properly manage nozzle flow rate.

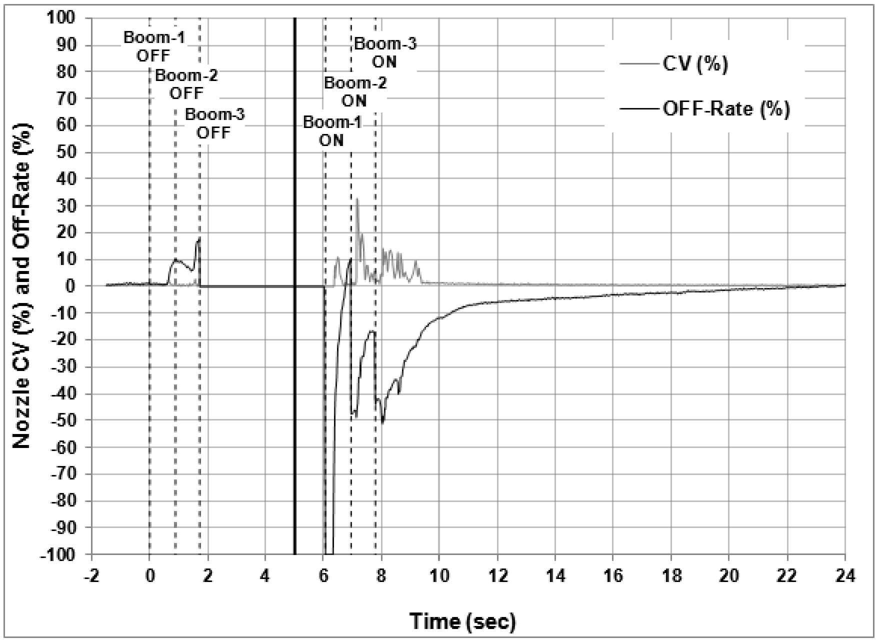


Figure 5.9. Nozzle CV and off-rate (OR) for 20° point row ABC scenario with flow compensation.

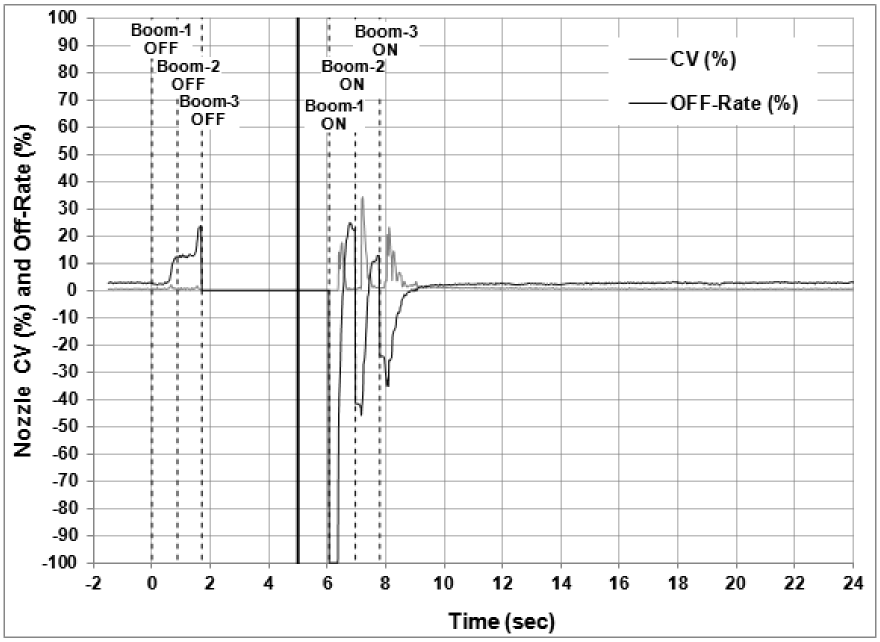


Figure 5.10: Nozzle CV and off-rate (OR) for 20° point row ABC scenario with no-compensation.

5.4.3 AUTO-NOZZLE, 20° AND 70° POINT ROWS - WITHOUT FLOW COMPENSATION

For 20° and 70° point rows, the time interval of sending the input signal to an individual nozzle solenoid was much shorter compared to 20° auto-boom scenario (Table 5.2). It took a total time of 2.5 and 18.7 s to exit and reenter the 20° and 70° point rows, respectively. The nozzle flow rate linearly dropped and rose at 17.7 L/min/s for 20° (Figure 5.11) and at 2.3 L/min/s for 70° (Figure 5.12) point rows during exit and reentry. The off-rate increased from + 3.7% to 28.7% both for 20° and 70° point row tests during exit and decreased during reentry. Since the control point was at each nozzle body, the effect of shutting OFF of each nozzle solenoid was almost immediate. This result was expected since for each nozzle solenoid shut OFF had an associated small volumetric change (1.14 L/min) in the system flow rate. This volume partially contributed to increase in nozzle off-rate, until the nozzle flow rate reached its maximum capacity.

The nozzle uniformity had short duration spikes up to 65.0% during point row reentry and was shorter in duration as compared to ABC. These high CVs were attributed to nozzle solenoid activation times (< 100 ms) to stabilize during reentry. There would actually be 37 such spikes had there been a pressure sensor at all 37 nozzles. The high nozzle CVs are missing when exiting because once a nozzle section was OFF that section was excluded from analysis and nozzle flow rate in the remaining ON sections across the boom increased instantaneously. The system behavior was similar to auto-boom tests with no-compensation (Figure 5.8 and Figure 5.12) though the linear rise and fall in nozzle flow rate using nozzle control can result in more over-application, both during exit and reentry into point rows.

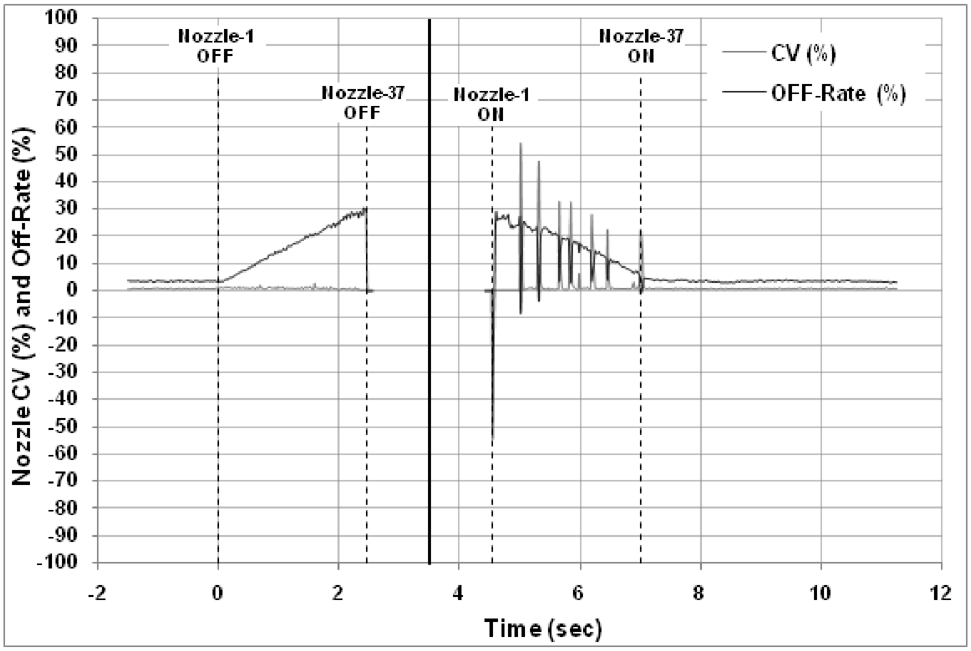


Figure 5.11. Nozzle CV and off-rate (dotted lines showing only the when nozzle 1 and 37 are turned ON or OFF) for 20° point row ANC with no-compensation.

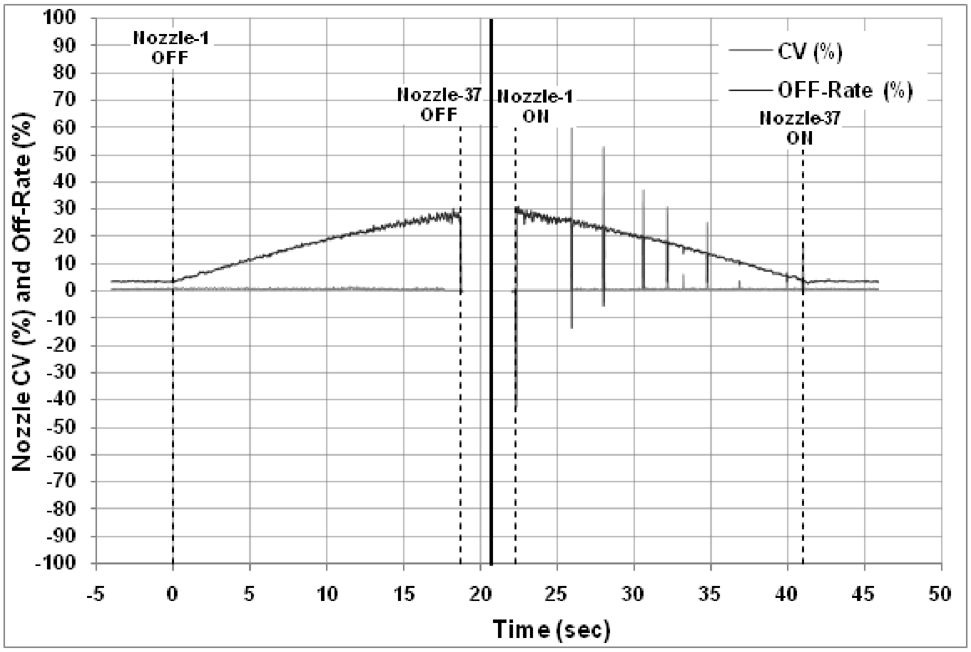


Figure 5.12. Nozzle CV and off-rate (dotted lines showing only the when nozzle 1 and 37 are turned ON or OFF) for 70° point row ANC with no-compensation.

5.5 SUMMARY

This study highlighted the control system response and extent of nozzle off-rate when using ASC in point rows. The control system response time to manage nozzle flow rate (settling time) was higher than expected especially during reentry of the 3rd boom-section. Also, for point row angle of 20° the control system did not respond fast enough to manage nozzle flow rate with changing boom-section configuration. During auto-nozzle tests the nozzle off-rate increased for each nozzle exiting and reentering point rows. Since the nozzle to nozzle spacing on this sprayer was 0.51 m, the nozzles exited and reentered point rows much faster than boom-sections having 6.2-m width. The nozzle off-rate response from auto-nozzle tests suggested that with increasing demand on decreasing application resolution, control systems with response times faster than section turning OFF/ON is required to minimize application errors. One overriding results is that as the point row angles decrease so does the demand on the control system to respond quicker. However, at some point, the response demand is too high or unrealistic and it might be better for the control system to look-ahead to its final control point during ASC activation versus trying to provide real-time flow adjustment. We do recognize that field operation will present entirely different scenarios and demands on sprayer control technology. However, this study does highlight limitations that need to be considered for sprayer control and technology design to ultimately minimize off-rate errors and spray efficacy.

5.6 CONCLUSIONS

The following conclusions were drawn from this study:

- For auto-boom control tests with flow compensation, nozzle flow rate settling time varied from 0.4 to 14.4 s for 70° point rows. For 20° point rows, the time of switching boom-sections OFF/ON occurred too abruptly for the control system to respond in a timely fashion. However, the nozzle flow settled in 13.0 s once all three boom-sections were ON for the 20° tests. Extended nozzle flow settling times indicated that longitudinal (direction of travel) off-rate errors can occur for an unexpectedly higher period of time during point row operation than expected.

- Nozzle off-rate varied between -36.6% and 10.7% for the 70° point row auto-boom tests with flow compensation; both exiting and reentering point rows. System dynamics were different between exiting versus reentry of point rows for all tests. Over-application occurred for roughly 12.0 s when exiting whereas under-application resulted for 13.0 s during reentry for the ASC system tested.
- The no-compensation tests showed that nozzle flow settled quickly (0.1 to 2.0 s) but resulted in over-application errors up to 21.3% for auto-boom and 28.7% for auto-nozzle control tests. Therefore, control system response with compensation was distinctly different from no-compensation.
- Nozzle uniformity (CVs) were within 1.0%, however spikes in CVs greater than +50% occurred for a short duration (< 1.0 s) during point row reentry for both auto-boom both during compensation and no-compensation tests and auto-nozzle control tests.
- Similar to other spray technologies, ASC with flow compensation managed nozzle flow rate and off-rate, but under the limitation of the control system response time. The control system can be modified to provide a level of improved response and for other situations like 20° point rows, by deploying a look ahead feature to control final point during ASC to minimize off-rate errors.

CHAPTER 6

EFFECT OF AGRICULTURAL SPRAYER FLOW CONTROL HARDWARE ON NOZZLE RESPONSE

6.1 ABSTRACT

Modern rate controllers along with technologies such as automatic section control (ASC) can improve in-field input use efficiency while preventing detrimental effect of unwanted spray application in areas such as grassed waterways or other environmental structures. However, the understanding of product (liquid) dynamics within the boom plumbing on off-rate and application uniformity during rate control and ASC actuation is limited. Therefore, a study was conducted to compare nozzle flow stability and uniformity across the boom when using two boom (2-way and metered 3-way) and two flow regulating (butterfly and ball) valves combinations. Tests were conducted using a 18.3 m sprayer with boom-section control. 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 valve response was significantly different as compared to metered 3-way valve. Differences were also indicated by the damping ratios when exiting (under-damped) and reentering (over-damped) spray zones. For the metered 3-way boom valve configuration, the nozzle flow settled faster (0.1 to 4.2 s) generating negligible off-rate errors whereas the 2-way boom valve configuration took up to 34.3 s to settle with off-rate errors between 3.3% and 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 s to 19.3 s) and metered 3-way (2.1 to 4.4 s) boom valves setups. Further, the varied nozzle flow settling times using the butterfly (1.0 to 23.7 s) and fast (0.4 to 15.6 s) regulating valves indicated that one valve calibration number (VCN) may not apply to all sprayer configurations and field operations.

6.2 INTRODUCTION

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 and efficiency but also include control systems to accurately apply crop inputs. Recently, self-propelled agriculture sprayers have grown in size with nominal boom widths of 27 or 39 m with operating ground speeds nearing 32 km h^{-1}. These large sprayers are being adopted by farmers to cover more area in less time in order 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 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 either utilize a ground speed radar (Tompkins et.al., 1985) or a global positioning system (GPS) receiver to monitor ground speed and regulate system flow necessary for that ground speed. Therefore, as ground speed changes, the rate controller adjusts the system flow to maintain the set target rate (L ha^{-1}). The system flow rate or application rate is managed through some type of flow control configuration which is typically comprised of hardware like an inline flow meter, flow regulating valve and boom shut-off valves. Today, a control system utilizing GPS and section control capabilities can automatically turn boom-valves and thereby sections ON or OFF independently. The flow control system with such 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 across the field. 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 sprayed 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 valve is of particular importance. Two general types of boom shut-off valves exists; 2-way (ON/OFF) or 3-way which includes 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 U.S. 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 is 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. The regulating valve response time and characteristics are dictated by selecting a valve calibration number (VCN) which is programmed by the operator in the control system. During ASC actuation and ground speed changes, the control system uses feedback from the inline flow meter and controls the system flow rate via the regulating valve or pump speed to maintain the target application rate. The system thereby automatically implements flow compensation. 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, the 3-way boom valve has one inlet and two outlets. One outlet goes to the boom-section while the second is connected such that it returns flow 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 ON sections. A metered 3-way boom valve is a specific type of 3-way valve that has an integrated user adjustable bypass dial to re-direct the product flow of the boom-section turned OFF back to tank (Teejet, 2011). Once calibrated, the metered product is returned to tank when in off-state. Therefore, during ASC actuation the boom-valves permits a constant pressure to be maintained regardless of the boom valve state (on or off). However, a metered 3-way boom valve setup still requires flow feedback to the controller to properly manage system flow for sprayer acceleration or deceleration.

With a projected U.S. spending 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, flow control configuration response time to timely manage system flow rate is critical for application accuracy. Therefore, the objectives of this study were to 1) compare and contrast the performance of 2-way and metered 3-way boom valve configuration on overall application accuracy, and 2) evaluate the effect of flow regulating valves including valve calibration number on nozzle flow response during ASC actuation.

6.3 MATERIALS AND METHODS

6.3.1 SPRAYER AND FLOW CONTROL SYSTEM

A three-point hitch mounted agricultural spray boom (Schaben Industries, Columbus, NE, USA) with a 18.3 m swath width served as the platform for conducting this study. The sprayer was operated in a static position using water. It utilized a centrifugal pump (FMC-150-HYD-206, ACE Pumps Corp., Memphis, TN, USA) that was hydraulically driven by a tractor (6420, Deere and Company, Moline, IL USA). The dry-boom setup was divided into three sections with plumbing and identification provided in

Figure 6.1. Turbo Teejet flat spray nozzles (TeeJet TTI11003 Spraying System Co., Wheaton, IL, USA) were used for these experiments.

A commercially available Raven Viper-2 spray controller was also used for the two flow control configurations. Flow control configuration-1 used a turbine-type flow meter (RFM-60P, Raven Ind., Sioux Falls, SD, USA); 2.54-cm butterfly type regulating valve (063-0171-120, Raven Ind., Sioux Falls, SD, USA) to adjust overall system flow rate and; 2-way boom valves (1-063-0172-330, Raven Ind., Sioux Falls, SD, USA) to turn ON or OFF flow to each of the three boom-sections (Figure 6.1). The initial setup used a valve calibration number (VCN) of 2123 for the regulating valve as suggested in the manufacturer's product literature (Table 6.1). An auxiliary flow meter (FM-1) (FT-16-NEXW-LEG-5, Flow Technology Inc., Tempe, AZ, USA) 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.

Table 6.1. Definition of the 4-digit valve control number (VCN) for each flow regulating valve.

Digit	Parameter	Control characteristic	Butterfly valve	Fast valve
1st	Valve Backlash	Controls the time of the first correction pulse after it detects whether to increase or decrease the target flow	1(short pulse) to 9 (long pulse)	0 - No pulse
2nd	Valve Speed	Controls the speed of response	1 (slow) to 9 (fast)	0 (fast) to 9 (slow)
3rd	Brake Point	Controls at what percentage away from target rate, the valve starts slowing down before adjusting to the target rate	Value between 0 to 9 where 0 = 5%, 1 = 10% and 9 = 90%	
4th	Dead-Band	Determines the allowable difference between target and actual application rate	Value between 1 and 9 where 1 = 1% and 9 = 9%.	

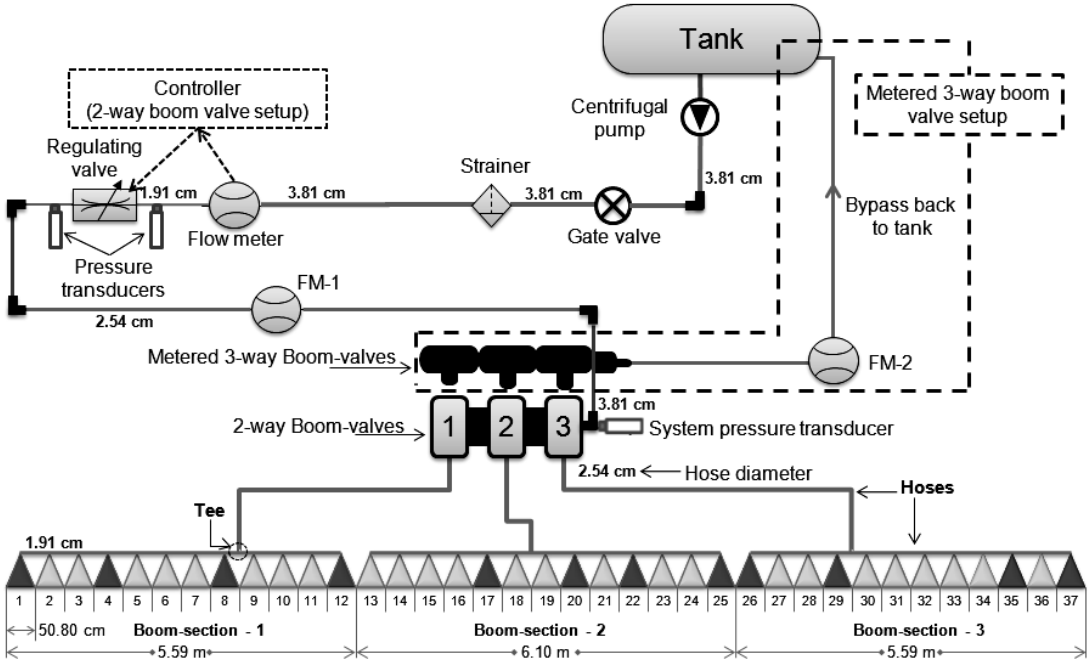


Figure 6.1. Sprayer configuration and plumbing for the 2-way and metered 3-way boom valve configuration. Each nozzle location, represented by triangles, was numbered between 1 and 37 from left to right. Four pressure transducers were mounted within each boom-section as represented by the solid black 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 control configuration-2 consisted of replacing the 2-way boom valves with metered 3-way boom valves (Model DS-430EC-3, Teejet Technologies, Wheaton, IL, USA; Figure 6.1). The 3-way boom valves utilized an adjustable bypass mechanism to match the pressure to a boom-section. The bypassed product was returned to tank when the boom-section was turned OFF. Since this setup did not require rate adjustment when turning sections ON and OFF, the flow regulating valve and flow meter were not used during flow control configuration-2 tests. System flow or pre-determined target pressure was set prior to initiating a test and thereby not adjusted once a test was initiated. Proper setup procedures of these boom valves included setting the dials initially to the "zero" position when all sections were turned ON to spray at 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) (FT-16-NEXW-LEG-5, Flow Technology Inc., Tempe, AZ, USA) was placed in the bypass line between the metered 3-way boom valves and tank (Figure 6.1). 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.

6.3.2 DATA ACQUISITION

Thin film pressure transducers (1502 B81 EZ 100 PSI G, PCB Piezotronics Inc., Depew, NY, USA) were used to measure nozzle pressure at 12 nozzle locations across the spray boom (Figure 6.1). 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 collect overall system pressure. This location was the same as where the analog pressure sensor, providing feedback to the operator, was connected. One pressure transducer was also mounted immediately upstream and another downstream of the regulating valve to measure the pressure drop across the valve (Figure 6.1). The analog signals from the pressure transducers, three boom valves and flow meters were sampled using two analog input modules (9221, National Instrument, Austin, TX, USA). The boom-sections were turned OFF and ON using an input signal from digital output modules (9476, National Instruments, Austin, TX, USA). The digital output signals controlling each boom valve (on and off state) was accomplished using input/output modules (70G-ODC15, Grayhill Inc., La Grange, IL, USA). A program in LabVIEW (version 8.6) was developed to record the control and data acquisition aspects which included writing all data to a *.TXT file at a 40 Hz sampling frequency.

6.3.3 Experimental Design

6.3.3.1 Boom-valve tests

Flow control configuration-1 and -2 were used to evaluate nozzle flow stability and response across the boom when using ASC (of boom-sections) during typical field scenarios. Tests were conducted simulating sprayer ASC actuation when exiting and reentering point rows at three angles; 20°, 45° and 70° (Figure 6.2). 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 making 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-1were 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 was 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 6.2). The theoretical time required to actuate each boom-section when exiting and reentering spray zones was calculated based on ground speed, boom-section width and point row angle (Table 6.2). 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 (Figure 6.3).

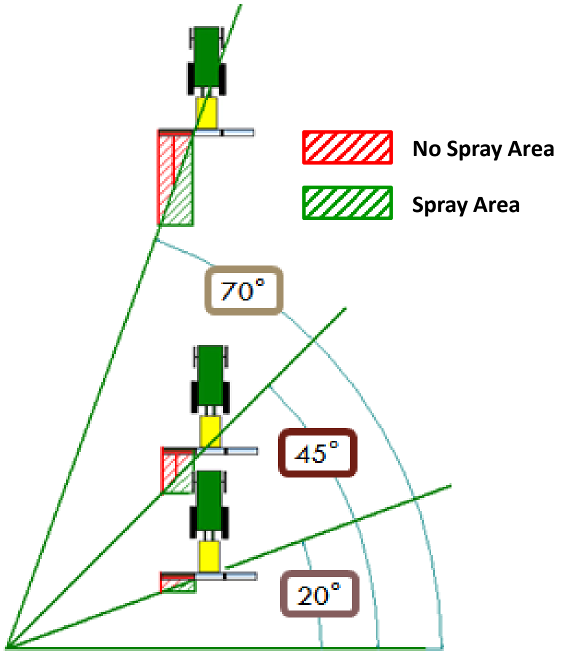


Figure 6.2. Illustration of sprayer exiting point rows.

Table 6.2. 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. Note, section 2 has one additional nozzle versus sections 1 and 3 therefore required different timing and rate for these point row scenarios.

Point row angle	Ground speed (km h^{-1})	System Pressure (kPa)	Sections 1 and 3		Section 2	
			Time (sec)	Rate (L min^{-1})	Time (sec)	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

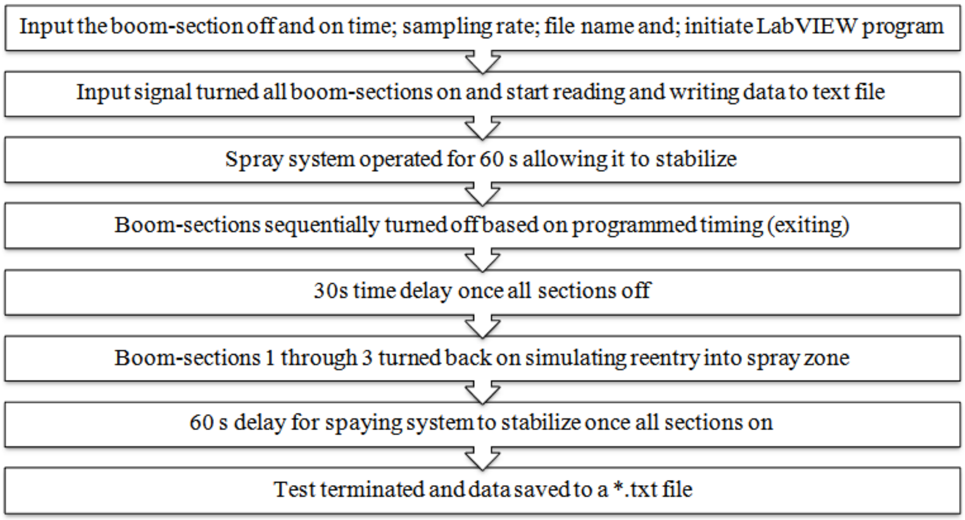


Figure 6.3. Data collection procedure for the LabVIEW program.

6.3.3.2 Regulating valve tests

Flow control configuration-1 tests consisted of using both the butterfly and fast ball flow regulating valves. For test involving the fast valve, the butterfly valve in flow control configuration-1was replaced with a fast ball regulating valve (Model No. 063-0171-265, Raven Ind., Sioux Falls, SD, USA) using an initial VCN 0743. Two VCNs, 2123 and 2213, for the butterfly valve along with five, 0633, 0643, 0713, 0723 and 0743, for the fast ball valve were selected. The valve backlash (1st digit) and dead band (4th digit) valves were kept the same for all tests. For the butterfly valve, VCN 2123 was initially selected since recommended by the manufacturer and a second VCN 2213 which increased the valve speed by one digit and decreased the break point from 20% to 10% was selected for comparing the response to the standard VCN. The manufacturer recommended VCN for the fast ball valve was 0743. The valve was set at a C-FC (Fast close) valve settling within the rate controller. The other four VCNs were selected by increasing the valve speed by one digit and selecting break point digits of 1, 2, 3, and 4 allowing evaluation of the regulating valve response during different tests. Tests were conducted by turning one (1BS) or two consecutive (2BS) boom-section(s) OFF and then back ON. Additional tests were also conducted to quantify the regulating valve response to sprayer acceleration and increase in target rate. For the acceleration tests, the controller was set to spray at a 84.2 L ha^{-1} target rate with the ground speed changed from 9.7 to 16.1 km h^{-1}. The target rate increase tests were conducted by increasing the rate from 74.8 to 140.3 L ha^{-1} while maintaining a ground speed of 9.6 km h^{-1}. All the boom-sections were turned ON and allowed to run for 60 s prior to conducting a test allowing the operating conditions within the plumbing to stabilize.

6.3.4 DATA ANALYSES

Measured nozzle pressure was converted to flow by fitting a second order polynomial regression line (Equation 6.1) to the manufacturer's reported nozzle pressure-flow data (Teejet, 2008). Nozzle flow was only calculated for those boom-sections which were operating in the on-state during a test. A MATLAB program was developed and 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 (NF-ST), 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.

$$\boldsymbol{Nozzle\ flow} = -\mathbf{2} * \mathbf{10^{-5}}(\boldsymbol{pressure^2}) + \mathbf{0.0059}(\mathbf{pressure}) + \mathbf{0.1003} \quad (\mathbf{R2} = \mathbf{0.999}) \qquad \textbf{(Equation 6.1)}$$

The percent difference between actual accumulated nozzle flow and target system flow was calculated and termed, nozzle off-rate. The damping ratio was a parameter 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 stable value to the time when it finally settled and stayed within ±2% of final flow rate after the boom-section(s) was turned OFF or back ON. 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. Flow rate error (FRE) was calculated for the regulating valve tests. FRE represented the difference in the accumulated nozzle flow and system flow at any time stamp during a test. For illustrations, flow data from only one nozzle within a boom-section was selected.

An analysis of variance (ANOVA) was conducted in the Statistical Analysis System software (SAS Institute, Inc. NC, USA) using the General Linear Model (GLM) procedure to ascertain if statistical differences existed between the different 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 NF-ST, damping ratio, ORT and total ORT for all tests were conducted using the Tukey-Kramer procedure.

6.4 RESULTS AND DISCUSSION

6.4.1 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 Table 6.3 and Table 6.4; along with Figure 6.4. The 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. 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. For reentry, the nozzle flow settled between 13.4 and 34.3 s after the 3rd boom-section was in the spray zone (Table 6.4). The NF-STs decreased as the ground speed increased when exiting, whereas for reentry it increased with ground speed (thereby target system flow) and also 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 (Figure 6.5). 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 different tests which demonstrated that the valves response time is critical when managing nozzle flow.

Table 6.3. Summary of nozzle flow response and pressure damping ratio (ζ) when exiting a spray zone. [a]

			Booms OFF								
			1				1 & 2				
Angle	**Valve**	**Speed (km h^{-1})**	**OR (%)**	**NF-ST (sec)**	**ζ**	**ORT (sec)**	**OR (%)**	**NF-ST (sec)**	**ζ**	**ORT (sec)**	**Total ORT (sec)**
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, NF-ST=nozzle flow rate settling time, ORT=off-rate time, and Total ORT=total off-rate time (ORT: 1boom OFF + ORT: 1&2 boom OFF). Within columns, means followed by the same letter are not statistically different at the 95% confidence level.

- nozzle flow did not varied beyond ±2% of initial value.

Table 6.4. Summary of mean nozzle flow response and pressure damping ratio (ζ) when reentering a spray zone.[a]

			Booms ON				
			1	1 & 2	1, 2 & 3		
Angle	Valve	Speed (km h^{-1})	ORT (sec)	ORT (sec)	NF-ST (sec)	ORT (sec)	Total ORT (sec)
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 ; NF-ST=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). Within columns, means followed by the same letter are not statistically different at the 95% confidence level.

The nozzle pressure damping ratio varied from 0.5 to 0.8 exhibiting a second order under-damped system when exiting the spray zone. The higher damping ratio corresponds to smaller oscillations within the system plumbing and faster system stabilization. The lower damping ratio (0.5) therefore explained the higher settling time (1.3 s) for the 9.6 km h^{-1} test. The damping ratio increased with increase in ground speed but the point row angle did not impact the damping ratio when exiting. The system response was a second order over-damped response ($\zeta > 1$) during 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 quick but generated off-rate between 3.3% and 11.5% when exiting spray zones. The nozzle off-rate increased between turning one and two boom-sections (ASC actuation) off when exiting. Also, for both 45° and 70° point row angles, the 2 higher speeds generated off-rate errors above 10%. During reentry to spray zones, the nozzle off-rate was within ±5% only after all three boom-sections were in the spray zones. The ORT (0.6 to 5.0 s) for 2-way boom valve increased with speed, except that the ORT was highest at 12.1 km h^{-1}, when exiting spray zone (Figure 6.5). 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} at 70° angle of incidence (Figure 6.6). 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 (Figure 6.7).

The nozzle flow did not 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 (Table 6.3) for the metered 3-way valve (Figure 6.4). 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 (Figure 6.4 and Figure 6.5). During spray zone reentry, nozzle flow settled between 0.9 and 4.2 s but only after all three boom-sections were completely in the spray zone and all sections turned ON (Table 6.4). 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 nozzle flow settling time was comparable when exiting but it decreased with ground speed and point row angle when spray zone reentry. The total ORT when reentering decreased with increase in ground speed but increased at higher point row angles, except that it was highest at 12.1 km h^{-1} ground speed for all three point row angles (Figure 6.6 and Figure 6.7).

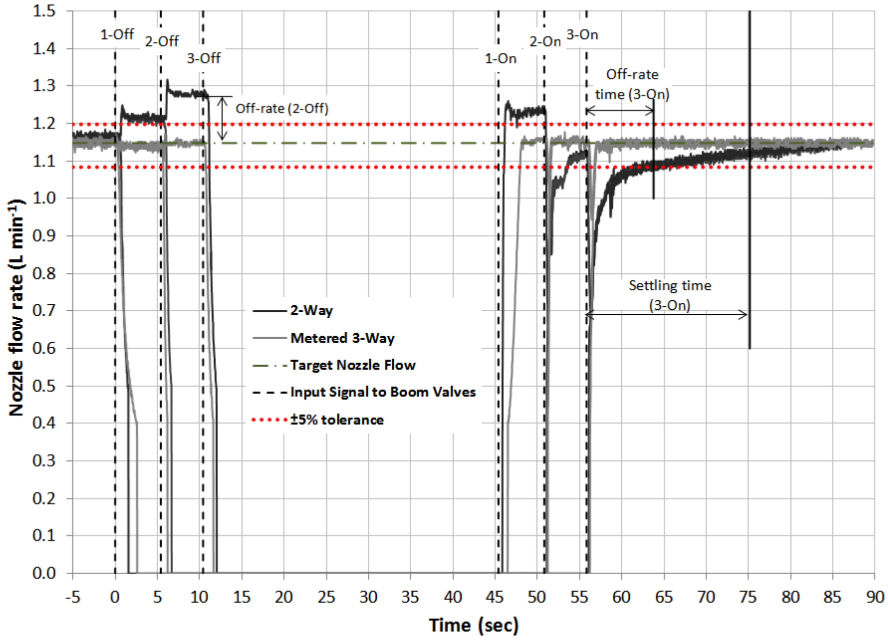


Figure 6.4. Nozzle flow response for the 2-way and metered 3-way boom valves when exiting and reentering 70 degree point rows at 12.1 km h^{-1} ground speed and 112.1 L ha^{-1} application rate.

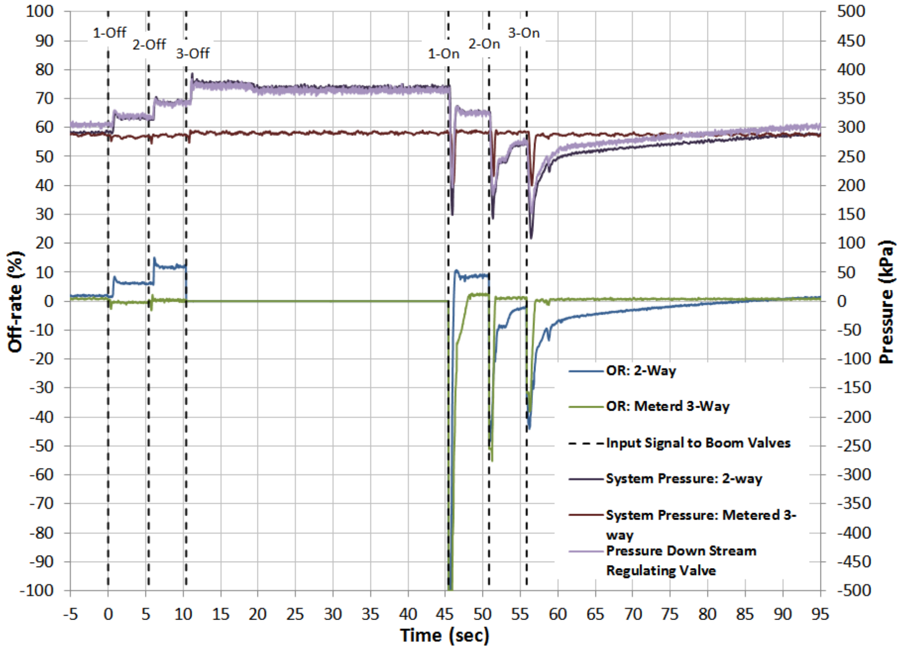


Figure 6.5. Pressure downstream of the regulating valve and nozzle off-rate for the 2-way and metered 3-way boom valve configurations when exiting and reentering 70 degree point rows at 12.1 km h^{-1} ground speed and 112.1 L ha^{-1} application rate.

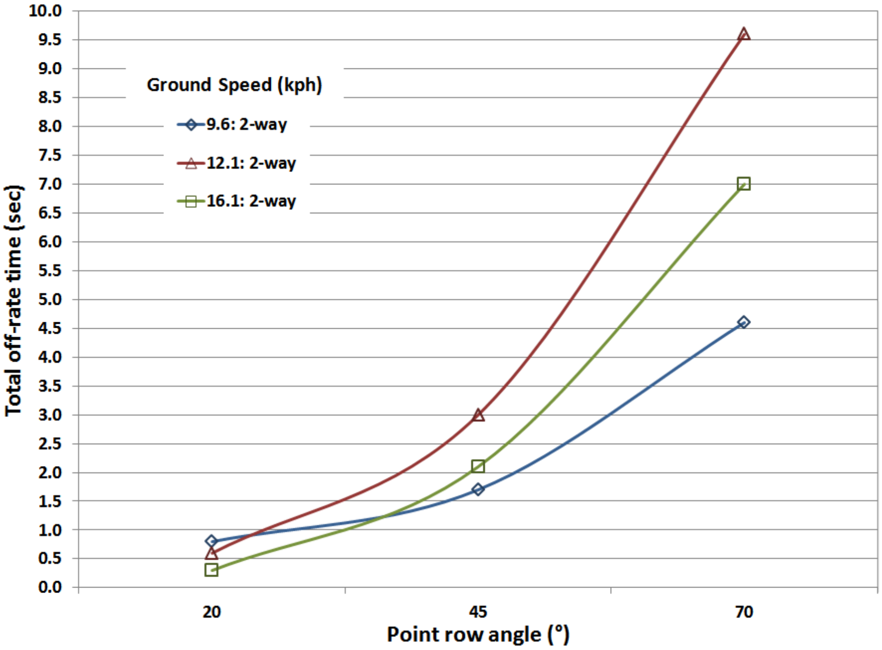


Figure 6.6. Total nozzle off-rate time at different ground speeds and point row angles for the 2-way boom valve configurations when exiting a spray zone.

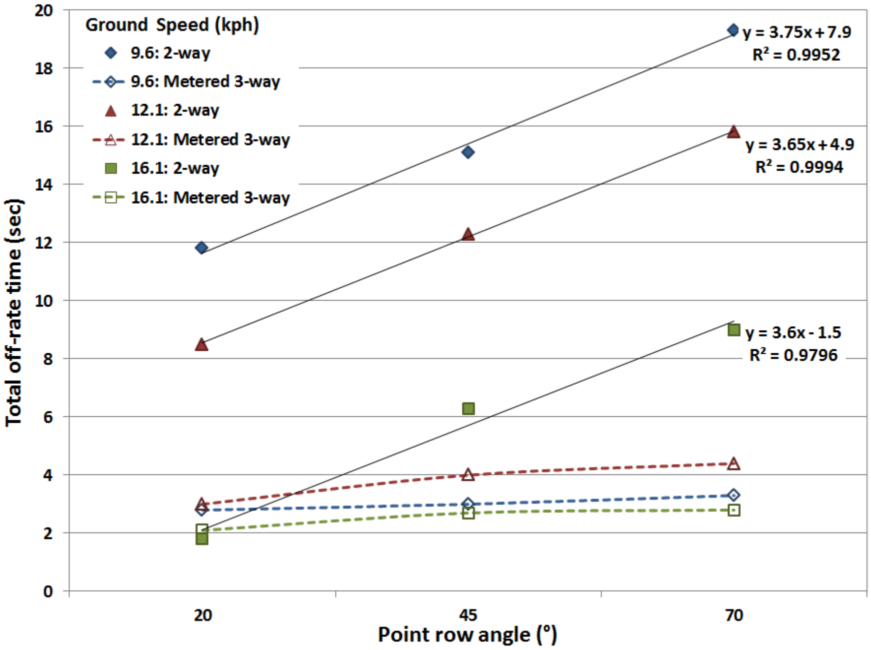


Figure 6.7. Total nozzle off-rate time at different ground speeds and point row angles for the two different boom valve configurations when reentering a spray zone.

Overall, results indicated that there was a distinct difference between 2-way and metered 3-way valve setups on nozzle flow response during ASC actuation. The time for consecutive boom-sections to exit and reenter a spray zone was less than one second for the 20° point row tests. Therefore, very short ON or OFF times highlighted response time limitations of a control system under certain operating conditions in managing nozzle flow within acceptable limits. For 45° and 70° point rows, the nozzle flow remained stable and settled significantly quicker (Table 6.3 and Table 6.4) resulting in short ORTs when using the metered 3-way valve setup (Figure 6.5). 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 maintained nozzle stability during ASC, it is suitable for tank mix applications. The boom-valves on the current agricultural sprayers are plumbed close to each boom-section. Therefore installing a 3-way will require additional hoses and plumbing to direct the flow back to the tank. The additional plumbing can thereby add weight on existing sprayers. Therefore, metered 3-way valve configuration poses different kind of challenges and requires U.S. operators accept this altered setup. Also the bypass dials on each boom valve was calibrated for setting a target system pressure by observing an analog pressure gauge requiring the operator to conduct the proper calibration procedure. The difference in nozzle flow response between flow control configuration-1 and flow control configuration-2 was expected since no rate change was required by the controller for flow control configuration-2. Interestingly, both flow control configurations generated distinct nozzle flow response at different ground speed and/or point row angle (Table 6.3 and Table 6.4).

Table 6.5. ANOVA results for nozzle flow settling time and off-rate during 2-way and metered 3-way tests at 45 and 70 degree point row angles[a].

Source	Degrees of Freedom	Sum of Squares	P-value
NF-ST 1-Boom OFF	11	6.58	<.0001
OR 1-Boom OFF	11	396.18	<.0001
NF-ST 2-Booms OFF	11	5.89	<.0001
OR 2-Booms OFF	11	889.81	<.0001
ζ 1-Boom OFF	5	0.08	<.0001
ζ 2-Booms OFF	5	0.25	<.0001
ORT 1-Boom ON	17	98.45	<.0001
ORT 2-Booms ON	17	69.35	<.0001
NF-ST 3-Booms ON	17	7312.80	<.0001
ORT 3-Booms ON	17	721.77	<.0001

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

6.4.2 REGULATING VALVE TESTS

The nozzle and system flow settling time for the two regulating valves, when using different VCNs, are presented in Table 6.6 through Table 6.8. The nozzle and system flow during 1BS and 2BS test using the fast ball valve settled between 0.3 and 1.0 s seconds but exhibited a 3.2 to 8.1% nozzle off-rate and 1.2 to 7.4% FRE when turning sections OFF. The system and nozzle flow settling time varied between 0.4 s and 2.9 s when the sections were turned back ON while nozzle off-rate was within ±2% (Table 6.6). During acceleration and the target rate change tests, the system flow took between 1.3 and 21.7 s to settle whereas the nozzle required 2.4 to 19.2 s to finally settle (Table 6.8). Flow control configuration-1 using the butterfly regulating valve settled nozzle and system flow between 0.7 and 25.2 s during boom control and from 3.8 to 20.4 s during speed and application rate change tests. The nozzle off-rate during these tests varied from 3.9 to 8.5% but the FRE was between 1.8 to 14.6%. The difference in nozzle flow settling times indicated that the ball valve responded faster as compared to butterfly valve, which was expected (Figure 6.8). The nozzle off-rate was slightly higher than the FRE for all VCNs for both regulating valves. The nozzle off-rate and FRE values indicated that a difference existed between the flow meter readings and actual nozzle flow rate during control system response for different tests. The actual system flow rate was within ±2% of the target flow rate and since the control system utilized feedback from the flow meter, the system could not correct the FRE. Therefore, control system feedback solely based on a flow meter, measuring system flow, appears to be insufficient at times to accurately identity and manage the actual flow at the nozzle.

The increase in valve speed and decrease in brake point digits decreased the nozzle and system flow settling time during acceleration and target rate change tests. The nozzle flow settling time during acceleration tests decreased from 19.5 s (0743) to 15.6 s (0643) by changing the speed digit from 7 to 6. The nozzle flow settling time decreased from 19.2 s (0743) to 3.6 s (0713) by changing the break point digit from 4 (40%) to 1 (10%) when changing the rate. The fastest system and nozzle flow response during dynamic speed and application rate change tests occurred when using VCN 0713. The flow settling time decreased when the speed digit was changed from 1 to 2 and break point digit from 2 to 1 for all the tests using the butterfly regulating valve (Figure 6.8). The increase in valve speed and decrease in break point significantly improved the regulating valve response by decreasing the response time (e.g. settling time). This result highlighted that the VCN can impact nozzle response (Figure 6.9). Finally, no single VCN provided least nozzle flow response time during rate change tests. This suggests that control system need to automatically select a VCN which is appropriate for intended nozzle response.

The operator usually selects a VCN as recommended for the regulating valve. Once the VCN is programmed in the controller the operator very rarely changes it. Since the VCN dictates the regulating valve response, these tests highlighted that determining VCN number for a specific sprayer configuration and minimizing spray application errors can be difficult for the operator. One future solution would be the ability of the spray control system to automatically establish the appropriate VCN for a sprayer and its plumbing, nozzles, operator aptitude, and field conditions. In this automatic establishment (auto-tune) of the VCN, the control system would have the capacity to collect or monitor the system response. The system response could be ascertained using the flow meter in combination of a pressure transducer(s) or other instrumentation. In return it then uses this information to understand the system and nozzle response and finally sets the VCN to minimize off-rate errors. This automatic selection of the VCN might be helpful for a sprayer setup which uses third party control system. The VCN could also dynamically change as operating conditions or the response changes. The control system could also have self-test procedure which be used during setup and calibration. The self-test might run the system at the target application rate and perform a system response test by iteratively selecting different VCNs identify which VCN provides the desired response time.

Table 6.6. Summary of system and nozzle flow for both the butterfly and fast ball valve using different VCNs when 1 boom-section was turned OFF then back ON. [a]

VCN	-------------- 1 Boom OFF ---------------				1 Boom Back ON	
	SF-ST (s)	NF-ST (s)	OR (%)	FRE (%)	SF-ST (s)	NF-ST (s)
633	0.3	0.7	3.2	2.9	0.8	0.4
643	0.3	0.6	4.3	2.7	0.8	0.4
713	0.5	0.7	4.4	2.8	0.6	0.4
723	0.5	0.7	3.2	1.2	0.5	0.4
743	0.5	0.8	5.1	3.2	0.9	0.4
2123	0.7	1.0	5.9	4.1	12.4	11.3
2213	0.7	1.1	3.9	1.8	6.6	9.1

[a] SF-ST=system flow settling time; NF-ST=nozzle flow settling time; OR=off-rate; FRE=flow rate error.

Table 6.7 Summary of system and nozzle flow results for the flow regulating valves when using different VCNs. Data represents when 2 boom-sections (1 and 2) are concurrently turned OFF or back ON while section 3 remains ON the entire duration. [a]

VCN	------------- 2 Booms OFF -------------				2 Booms Back ON	
	SFR-ST (s)	NF-ST (s)	OR (%)	FRE (%)	SF-ST (s)	NF-ST (s)
633	0.5	1.0	6.0	5.0	1.0	0.6
643	0.7	1.0	7.3	6.9	1.0	0.8
713	1.0	1.0	7.7	7.4	1.2	1.0
723	1.0	1.0	7.1	6.0	2.9	0.7
743	0.6	1.0	8.1	3.1	1.2	2.4
2123	25.2	23.7	8.5	4.3	18.3	16.6
2213	13.6	11.3	7.9	1.0	9.7	11.7

[a] SF-ST=system flow settling time; NF-ST=nozzle flow settling time; OR=off-rate; FRE=flow rate error.

Table 6.8. Summary of system and nozzle flow response for the regulating valves with different VCNs when accelerating from 9.7 to 16.1 km h^{-1} or changing the target rate from 74.8 to 140.3 L ha^{-1}. [a]

	--- Acceleration ----				--------Target Rate Increase -------			
VCN	SF-ST (sec)	NF-ST (sec)	OR (%)	FRE (%)	SF-ST (sec)	NF-ST (sec)	OR (%)	FRE (%)
633	1.5	2.8	-0.4	-0.1	13.1	13.9	-1.5	0.3
643	15.6	15.1	-1.1	0.0	19.3	18.1	-1.7	-0.8
713	1.3	2.4	-1.0	-0.7	1.8	3.6	-1.2	-0.1
723	2.1	3.4	-0.8	-0.6	14.2	11.2	-0.9	0.3
743	19.5	15.6	-1.6	-1.3	21.7	19.2	-1.4	-0.5
2123	17.2	20.4	-0.1	2.1	9.3	17.4	-0.6	-1.4
2213	15.9	19.8	1.1	0.2	3.8	10.6	2.6	-0.4

[a] SF-ST=system flow settling time; NF-ST=nozzle flow settling time; OR=off-rate; FRE=flow rate error.

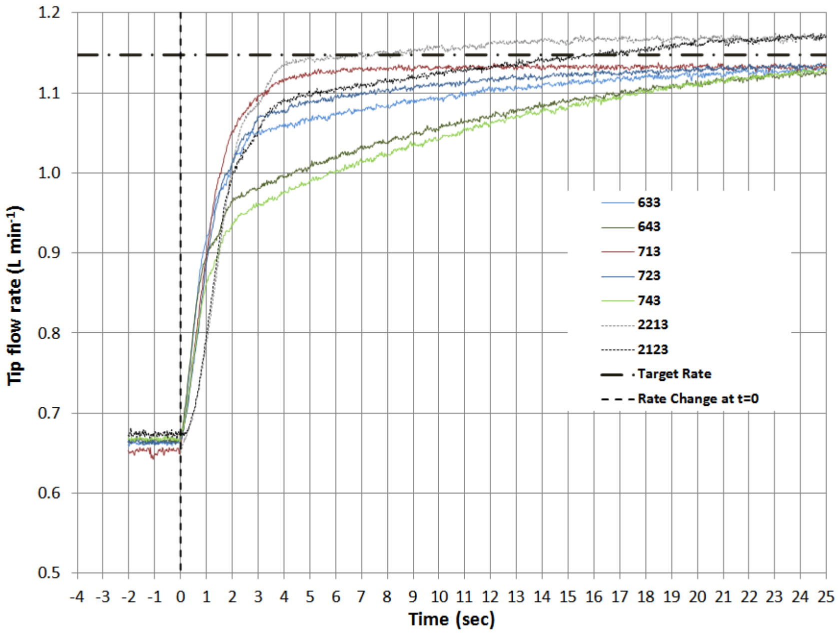


Figure 6.8. Nozzle flow response for the two regulating valves when using different VCNs. Results represent changing the target rate from 74.8 to 140.3 L ha^{-1} while maintaining a 9.6 km h^{-1}ground speed.

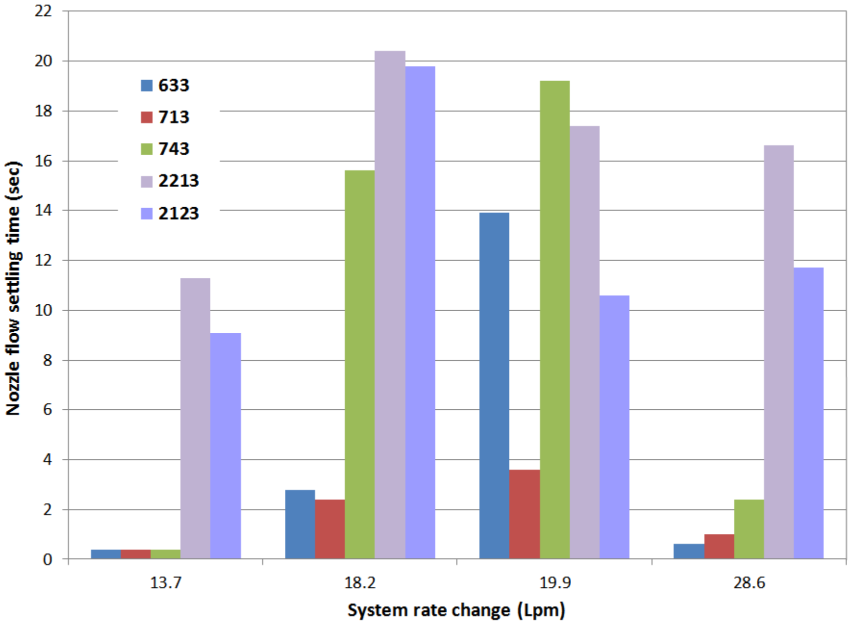


Figure 6.9. Nozzle flow settling time for system rate changes during 1-boom OFF to all booms back ON (13.7 Lpm), 2-booms OFF to all booms back ON (28.6 Lpm), response to acceleration (18.2 Lpm) and target rate change (19.9 Lpm) tests for different fast ball valve and butterfly VCNs.

6.5 CONCLUSIONS

The 2-way and metered 3-way boom valves impacted nozzle response significantly different. 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) plus negligible off-rate errors as compared to the 2-way boom valve setup which took up to 34.3 s to settle nozzle flow with off-rate errors between 3.3% and 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 tests.

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 3-way metered valve configurations because of control system response time limitations. 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.

The nozzle flow settling time also increased with increase in point row angle from 20° to 70° both 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 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.

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 valve setup when exiting and reentering spray zones. An exception was observed at 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. Nozzle flow response during different rate change tests was not optimal for any single VCN for the regulating valves. Also, an inconsistency between system and nozzle flow rate suggested that control system might include some additional feedback, such as nozzle pressure, apart from the current system flow meter to reduce off-rate errors. Further, an auto-tune feature could be integrated into future control systems to establish the appropriate VCN while minimizing off-rate errors.

CHAPTER 7
CONCLUSIONS

7.1 GENERAL CONCLUSIONS

The following conclusions were drawn from this research:

1) Both auto-nozzle and auto-boom control sprayers resulted in application errors beyond ±10% of the target rates. Off-rate errors were associated with ASC actuation and machine acceleration and deceleration during field operation. ASC actuation and ground speed variations altered the target system flow rate and the system flow settling to a new target depending on the control system response time. The incidence and magnitude of off-rate errors can vary with the shape of the field. For rectangular fields, the sprayer traveled near a constant speed with all control sections ON and the machine acceleration, deceleration and/or ASC actuation only occurred at the headlands. On the contrary, for irregular shaped fields, these machine parameters varied every time the sprayer approached and departed no-spray zones (e.g grassed waterways and other obstacles) and previously sprayed areas. These field conditions can place an extensive demand on the control system to respond quickly. Overall, variation in sprayer ground speed and number of control sections ON or OFF during ASC actuation both during static and field tests resulted in greater under-application (49% of time) than over-application (17% of time). Nozzle uniformity (CV) was normally below 10% except for short durations (0.2 to 0.5 s) when turning control sections ON and OFF. Overall, the static and field testing provided similar results.

2) The test methodology to record nozzle pressure, system flow rate and input signal to boom valves established basic techniques to evaluate real-time, dynamic nozzle response on agricultural sprayers. Nozzle pressure in the ON sections deviated (up to 20%) from the target value when turning boom or

nozzle sections OFF and then back ON. Nozzle pressure for both auto-boom and auto-nozzle tests was higher than the target pressure as control sections were turned OFF but lower when turning control sections back ON. The nozzle flow stabilized only after all control sections (e.g. full boom) were turned back ON and required several seconds to finally settle to the target pressure. The system flow rate settled relatively faster (7.0 s) as compared to nozzle pressure (up to 25.0 s). Additionally the nozzle flow was always higher (up to 11%) than the overall system flow measured by the flow meter. These results indicated a differential between the control measurement point (flow meter) and actual point of application (nozzle) as sections are turned OFF and ON. The nozzle pressure variation was less when using the flow compensation mode as compared to no-compensation. Although the nozzle pressure settled quicker for no-compensation, it was higher (up to 36%) than the target pressure at all times for both auto-boom and auto-nozzle section control tests. Finally, the difference in nozzle pressure increase and nozzle pressure response to switching control sections ON and OFF existed for auto-boom and auto-nozzle control tests. These results indicated that point of control (boom-section versus individual nozzle) can contribute towards boom flow dynamics during section control.

3) The control system response when moving OUT and back INTO point rows was distinctly different. When moving OUT of point rows, nozzle flow was greater than target rate generating over-application until all nozzles were turned OFF. Reentry back INTO point rows requiring application resulted in under-application until the final target stabilized once all nozzles were turned ON. The response of the control system when traversing INTO and OUT of point rows was impacted by the angle of incidence. The 70° and 20° results indicated that during field operation, the controller can practically manage nozzle flow only if sufficient response time was available between old and new target rate changes. However, during certain field scenarios requiring rapid flow response, the control system might exhibit a delayed or uncontrolled transient response. Nozzle uniformity (normally < 1%), and off-rate errors (-37% to 11%)

indicated that longitudinal (direction of travel) errors can occur for a longer period of time (up to 19 s) during point row operation.

4) Flow control configuration impacted nozzle pressure and flow dynamics. The metered 3-way boom valve configuration had no transient response during ASC actuation. On the contrary, the 2-way boom valve configuration exhibited under- and over-damped response for exiting and reentering point rows, respectively. Since, the metered 3-way boom valve simply redirected flow from boom-section(s) that were turned OFF back to the tank, nozzle flow settled quicker (0.1 to 4.2 s) as compared to the 2-way boom valve configuration (up to 35.0 s). Additionally for the 2-way valve setup, the nozzle flow settling time increased with point row angle both for exiting and reentering spray zones. Nozzle flow settling time increased with ground speed for reentering but decreased with increase in speed when exiting spray zones. As expected, the regulating valve VCN impacted nozzle flow settling times. However, the results for the butterfly and fast regulating valves indicated that different sprayer configurations and field operations may require controllers to dynamically establish the VCN for appropriate and acceptable system response. The total off-rate time provided a good measure to assess control system response to attain a new target nozzle flow during ASC actuation for point row operation. The total off-rate time increased at slower ground speeds in conjunction with higher point row angles for both the 2-way and metered 3-way boom valve setups.

7.2 FUTURE RESEARCH

The test methodology established for this research provided useful and quantifiable results as related to nozzle flow variability during spray applications. However, either existing standards or a new standard should be developed for agricultural sprayers to consider testing methodology and appropriate reporting to quantify response and delay times of individual flow control components such as the controller (e.g. control algorithm), regulating valve, boom shut-off valves and feedback sensors providing feedback within flow control system. These additions to standard testing protocol would establish the anticipated sources of errors during response and delay time, contributing to off-target applications. This knowledge of response and delay times would also help select appropriate components making a flow control configuration. Thus, future research should also focus on selection of control components and their placement regimen within boom plumbing to optimize control system response while minimizing off-rate application.

Hose compliance remains a relatively unknown factor impacting performance of agriculture sprayers. Hose compliance represents the ability of the sprayer plumbing (mainly hoses and tubing) to store and release energy in a manner leading to unknown effects on flow or pressure at the nozzles. Literature does not outline previous research on hose compliance related to agricultural sprayers and it was not an aspect studied in this research. However, results in which the flow meter estimates did not align with nozzle flow for short periods of time could suggest that hose compliance was a contributing element to this measured difference. Agricultural sprayers typically use a combination of flexible hoses and solid tubing. Understanding how the hose and tube respond to elevated pressure spikes for short periods and if they can store a portion of this energy is important pertaining to research, knowledge and design of new products. As reported in this research, response time during flow rate transitions either due to speed changes or ASC actuation needs to be reduced thereby minimizing off-rate errors. By quantifying and understanding hose compliance within sprayer plumbing, the design and management of agricultural sprayers and rate control technology can be improved to accurately and consistently maintain target rates.

Response time of controller to manage application rates during rate transitions depends on the response characteristics of flow control components. The response characteristics of components can be structured by appropriately programming within rate controllers. This programming of control components is also termed as tuning. This programming or tuning of control components is generally performed using manufacturer’s recommendations. Although we can expect operators to perform routine calibration procedures, the tuning and calibration of control components can become extremely difficult to execute. Improper tuning of the flow components can impact the response time of the control system generating off-rate errors as reported by this research. To overcome this limitation, additional research should be conducted on integrating features into the control algorithm to auto-tune flow control components versus the operator determining the appropriate setup. The auto-tune feature would properly program the control components through optimization techniques based on feedback from the flow meter, pressure transducers, or other sensors. The optimization would determine the proper speed of response and break point to maintain a stable transition while minimizing off-rate errors. Further, control components may demand unique tuning for varied field operating conditions and operator’s driving behavior. For example, headland operation might require different tuning from point row operation. Thus, research should also be conducted to add another level of control by classifying upcoming field response conditions as controllable or uncontrollable. For scenarios which are controllable, the controller should actively determine and dynamically tune components for optimum system response to minimize off-rate errors. Further, artificial intelligence incorporated into control software could help learn operator habits and driving characteristics along with sprayer plumbing behavior to adjust or tune the control system accordingly.

7.3 PRACTICAL IMPLICATIONS

The resolution of control on agriculture sprayers is becoming smaller based on new and soon to be released technology. In the past, application control across the spray boom was handled in sections (e.g. boom sections) with the number of individual sections increasing over the past few years due to the increased interest in automatic section control; as the number of sections increases so does the potential benefit of overlap reduction. Recently, companies are providing the capability to individually control nozzles further reducing the control resolution. Agronomic research is also investigating plant level management as a means to increase crop yields while decreasing input usage. Considering these aspects of technology and the thought of plant-to-plant management, spray application will require management at this resolution. While this concept and ability might be several years away, spray manufacturers and researchers are progressing towards this level of control resolution. The overall application accuracy of a rate control system largely depends on the selection of control hardware, flow control configuration, quality of feedback mechanism and response time of the system. Therefore, flow control components need to be carefully selected when designing a flow control configuration as it can impact nozzle flow response or off-rate errors. The response times of the flow control components such as the flow meter and regulating valve will need to be much quicker (at least 5x) than control section actuation in the future in order to maintain target rates. Quicker and improved response of spray technology is necessary if the agriculture spray industry wants to continue progressing towards small resolution of control. Another related point based on results of this research is that hardware controlling flow or pressure should be placed as close as possible to the boom-section or nozzles to reduce transient delays when managing nozzle flow. Improved technology and hardware will allow sprayer operators to not only maintain the target rate(s) but also adhere to product labels.

As pointed out in the research the system flow feedback might not truly represent nozzle flow, probably due to ability of the hoses to store and release energy (e.g. hose compliance). This disparity between nozzle and system flow may result in application rate errors especially when the controller assumes that the target flow has been achieved and no further adjustment is required. The feedback from point of application can provide accurate status of nozzle pressure during rate transitions. This information about nozzle pressure during transient times can offer better feedback for controller to accurately regulate system flow during transient times. Therefore, system feedback comprising of real-time system and nozzle pressure can provide more realistic data to the controller to better manage system flow.

One item often not discussed related to sprayers is how an operator perceives the use of technology. In general, once a sprayer is calibrated and tuned, an operator assumes the control system is responding to rate transitions in a fashion which maintains both the target application rate and desired droplet size. This perception is based upon feedback of the display to the operator since the display serves as the main if not the only mechanism to indicate how well the sprayer is performing. Therefore, if the display indicates the target rate is being maintained, then the operator assumes the sprayer is functioning properly. However, nozzle pressure can vary during ASC actuation and ground speed variations without the controller indicating off-rate could be occurring. This point was observed during field testing in this research in which the controller indicated acceptable performance while in reality off-target application was occurring. Therefore, the operator was unaware of this off-target issue. Further, the absence or difficulty of pressure feedback to the operator does not allow the operator to observe possible pressure variations during field operation. The selection of the appropriate spray tips is the first important step in spraying. Once selected, the range of acceptable pressures to maintain the desired droplet size and thereby spray efficacy needs to be monitored by the operator or controller.

To address these concerns, pressure feedback to the operator and into the controller to monitor variations and possible pressure levels outside the desired operating range is essential. Additionally, future rate controller should include algorithms to dynamically optimize component tuning and thereby stabilize nozzle pressure during rate transitions. Flow and pressure response is complex so having the capability of rate controllers to auto-tune will reduce application rate errors. This auto-tune feature will also reduce operator responsibility to make the decision on how to setup the rate controller (which is most likely a guess for most at this point) when it is unexpected for the operator to fully understand the complexity of pressure and flow behavior within the spray system.

The agriculture community is embracing the use of technology to improve the accuracy of input deposition. However, as technology advances, so does the understanding of spray behavior within the plumbing and the effect of hardware and software on sprayer performance to truly attain the concept of "precision" agriculture. Overall, future research and development of rate control technologies is needed to achieve accurate nozzle flow and product deposition on plants. Federal regulations require producers to follow product labels and the adoption of improved precision ag technologies to reduce off-rate errors can help address some of the issues today in the U.S., such as off-target applications, weed resistance and protecting environmentally sensitive areas.

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APPENDIX A

EVALUATION OF PRESSURE TRANSDUCERS

A.1 INTRODUCTION

Real-time nozzle pressure measurement is an important parameter to quantify control system response during laboratory or field experiments on the agricultural sprayers. This section outlines the procedure adopted to test the accuracy and consistency between different pressure transducers to measure nozzle pressure. Although, pressure transducers are designed to achieve consistently during measurement and subsequent control tasks, variability can exist between different units. This measurement variability needs to be quantified to determine a confidence band and highlight if any bias existed for the pressure transducer.

A.2 MATERIALS AND METHODS

A.2.1 INSTRUMENTATION AND SPRAY SYSTEM SETUP

Nozzle pressure data was collected using pressure transducers mounted on a test table and agricultural sprayer boom. Thin film pressure transducers (Model No. 1502 B81 EZ 100 PSI G, PCB Piezotronics Inc., Depew, NY, USA) were selected to measure nozzle pressure at 12 nozzle locations across the spray boom. The pressure transducers had measurement ranges of 0 to 689.5 kPa with a reported accuracy of ≤ 0.25% full scale and a response time of ≤ 1 ms. The analog signals from the pressure transducers were sampled using two National Instrument (NI) 9221 analog input modules. A program in LabVIEW (version 8.6) was developed to read and write pressure data to a *.TXT file at a 40 Hz sampling frequency.

The test table setup used a 12 V turbojet centrifugal pump, pressure regulating valve, pressure relief valve and 0.64 cm hose to produce water pressure at the nozzle end. Teejet 11003 (Teejet 2008) extended range flat spray tips were selected as nozzles. The nozzle and the two pressure transducers under evaluation were mounted on the stainless steel cross connector. This flow configuration allowed for achieving stable nozzle pressure up to 620.0 kPa.

Pressure transducers were also mounted on an 18.3-m agricultural sprayer (Schaben Industries, Columbus, NE, USA) in the Biosystems Engineering department at Auburn University. Another pressure transducer was mounted at boom-valve manifold to monitor system pressure. The sprayer was equipped with a centrifugal pump (FMC-150-HYD-206, ACE Pumps Corp., Memphis, TN, USA) that was hydraulically driven by a John Deere 6420 tractor (Deere and Company, Moline, IL USA). The spray control system utilized a turbine-type flow meter (Model No. RFM-60P, Raven Ind., Sioux Falls, SD, USA) and 2.54-cm butterfly type control valve (Model No. 063-0171-120, Raven Ind., Sioux Falls, SD, USA) to regulate overall system and nozzle pressure.

A.2.2 EXPERIMENTAL DESIGN

The pressure transducers were tested for consistency and accuracy when measuring tip pressure along the boom-section(s). A unique identification number between 1 and 24 was assigned to each of the pressure transducers. Five pressure transducers 5, 6, 8, 21, and 23 were randomly selected to be tests against a reference pressure transducer (number 22) on a test table. For each test, one of the five transducers was plumbed laterally on left side of cross pipe connector along with reference pressure transducers on the right side. Test were conducted by setting the target system pressure at 137.9, 275.8, 413.7 and 551.6 kPa to record nozzle pressure from two transducers simultaneously for 60 sec on a test table. The nozzle pressure data from a reference and each of the test transducer was analyzed to quantify the overall nozzle pressure measurement variability by two different transducers at the same location.

Tests were also conducted to measure nozzle pressure stability along a boom-section. For these tests 12 pressure transducers were randomly selected for each of the three replicated tests. The selected pressure transducers were mounted at nozzle locations 1 through 12 in the boom-section 1. The spray system was set to operate at simulate field settings of a 9.6 km h^{-1} ground speed and 112.1 L ha^{-1} application rate. The spray system was turned on and allowed to run for 60 sec to allow time for stabilization within the spray plumbing. Nozzle pressure data for the 12 nozzle locations and system pressure was recorded for 60 sec and then the system was turned off. The data was analyzed to compute overall nozzle pressure variability within boom-section using different sets of pressure transducers.

A.2.3 DATA ANALYSIS

Measured nozzle pressure data from tests was used to calculate the mean nozzle pressure, standard deviation, coefficient of variation (CV) and mean error. Means and standard deviations for different parameters were also calculated using the GLM procedure in Statistical Analysis System software (SAS Institute, Inc. NC, USA). Mean error between two pressure transducers was calculated in Microsoft Excel.

A.3 RESULTS AND DISCUSSION

The nozzle pressure measurement results are provided in Tables 1 and 2. The mean error between any two transducers measuring nozzle pressure varied between -2.9 and 3.8 kPa (Table A.1). The results highlighted overall nozzle pressure measurement accuracy of transducers. The pressure transducer comparison results demonstrated that mean nozzle pressure at 12 nozzle locations in boom-section-1 varied from 279.9 to 274.7 kPa. The variability in mean nozzle pressure during replicated tests was due to system pressure deviation between 291.0 and 284.8 kPa. The mean nozzle pressure exhibited standard deviation between 2.3 and 3.5 and CV from 0.9% to 1.2%. The results indicated that different pressure transducers, when located at a nozzle location along the boom-section, could measure nozzle pressure in a boom-section with a maximum CV of 1.2%.

Table A.1. Mean nozzle pressure error between different pressure transducers.

Target Pressure (kPa)	Mean Error (kPa)				
	PT[1]-8 & 22	PT[1]-23 & 22	PT[1]-21 & 22	PT[1]-6 & 22	PT[1]-5 &22
137.9	-0.9	0.2	0.7	2.7	-1.6
275.8	-2.9	0.3	3.8	0.3	-1.7
413.7	-2.0	0.6	2.3	1.8	1.1
551.6	-0.8	1.8	3.8	2.3	0.4

[1] PT=pressure transducer

Table A.2. Nozzle pressure consistency for different pressure transducers at five nozzle locations within a single boom-section.

Pressure transducer location	-----Test 1-----		-----Test 2-----		-----Test 3-----	
	PT-ID	NP (kPa)	PT-ID	NP (kPa)	PT-ID	NP (kPa)
SP	1	291.0	1	289.9	1	284.8
NL-1	5	282.0	6	277.0	15	268.9
NL-2	16	283.4	16	282.0	21	275.1
NL-3	15	277.2	12	284.8	12	276.5
NL-4	6	279.5	21	281.7	8	273.7
NL-5	14	279.9	14	278.6	14	273.7
NL-6	13	277.2	13	275.8	7	278.6
NL-7	12	282.6	11	278.1	13	272.4
NL-8	7	281.1	5	280.7	6	274.7
NL-9	21	278.8	15	273.2	16	275.1
NL-10	11	282.0	10	277.9	10	276.5
NL-11	8	276.5	8	275.8	11	275.1
NL-12	10	279.0	7	283.6	5	275.8
Mean (kPa)		279.9		279.1		274.7
SD (kPa)		2.3		3.5		2.4
CV (%)		0.8		1.2		0.9

[1] PT- ID=pressure transducer-identification number; SP=system pressure; NL=nozzle location; NP=nozzle pressure; SD=standard deviation; CV=coefficient of deviation

A.4 CONCLUSIONS

- The different pressure transducers were able to consistently measure nozzle pressure with a mean error from -2.9 to 3.8 kPa. The difference between the mean nozzle pressure and system pressure was approximately 10kPa.

- The nozzle pressure within the boom-section can be measured with standard deviation of up to 3.5 kPa and 1.2% coefficient of variation.
- The pressure transducers selected were therefore deemed sufficient for characterizing nozzle pressure on agricultural sprayers in this research.

APPENDIX B

HYDRAULIC HEAD DIFFERENCE DURING BOOM-SECTION TILT

B.1 INTRODUCTION

Boom-section roll can occur on rolling terrain during field applications. Thereby, boom-section roll or tilt can impact nozzle pressure can create hydraulic head differential due to differences in height between centerline of the boom-section and nozzle in the tilted boom-sections. This deviation in pressure due to boom-section tilt can result in non-uniform nozzle flow. However, there is no information about the actual and theoretical hydraulic head for implementing and studying boom-section tilt during field experiments. Therefore, tests were conducted to compare actual and theoretical hydraulic head during boom-section tilt of a 36.5 m wide auto-boom agricultural sprayer (Appendix-D.16).

B.2 METHODOLOGY

The tests were conducted using a common self-propelled sprayer (Appendix A.16). The sprayer was set on a level ground for static tests with spray boom unfolded and water as a spray liquid. Eighteen high frequency pressure transducers (Appendix B.10) were mounted across the spray booms (Appendix A.17) to record nozzle pressure. The spray system was set to apply at 161 and 310 kPa. For each system pressure setting the sprayer was allowed to run for 60 s to attain stable system pressure before tilting the boom-sections. In Scenario A left boom-section was tilted downwards and right boom-section tilted upwards whereas it was opposite for the Scenario B. The height of the boom from ground was measure at nozzle locations 1, 42, 48, 54 and 95 using a measuring tape. A National Instrument (NI) DAQ system was used to record analog input from pressure transducers using a program written in LabVIEW version 8.6. The nozzle pressure data at 10 Hz was written to a *.TXT file along with time stamps for analyses.

Figure B.1. Nozzle pressure measurement with left boom-section tilled upwards and right tilted downwards.

Figure B.2. Nozzle plumbing in the central boom-section.

B.3 DATA ANALYSIS

The actual height of each nozzle location from the ground was calculated using the measured height at 5 nozzle locations in Microsoft Excel. This height was used to calculate the theoretical hydraulic head.

The difference between nozzle pressure at the center of boom-section with boom-section in horizontal position and the actual nozzle pressure at eighteen locations during tilt scenarios were used to calculate actual hydraulic head.

B.4 RESULTS

The nozzle pressure at various locations for boom-section at horizontal position is presented in Figure B.3 whereas the comparison between actual and theoretical hydraulic head for Scenario A and Scenario B is presented in Figure B.4. The actual hydraulic head for the boom-section tilted downwards was greater than the theoretical while for boom-section tilted upwards was less than the theoretical head. The comparisons between the two hydraulic heads indicate that actual hydraulic head may differ from theoretical head. More experiments needs to be conducted to find a relationship between these two heads.

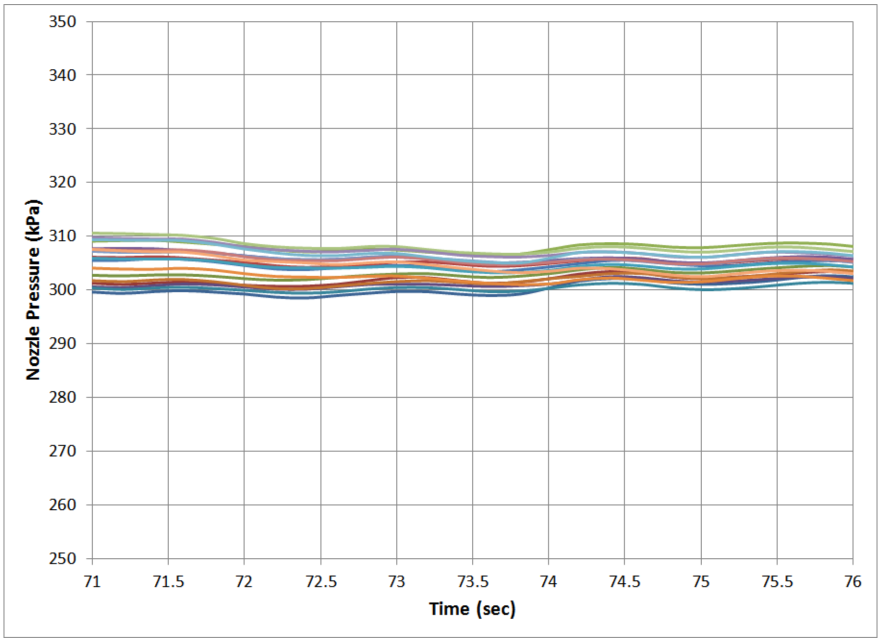
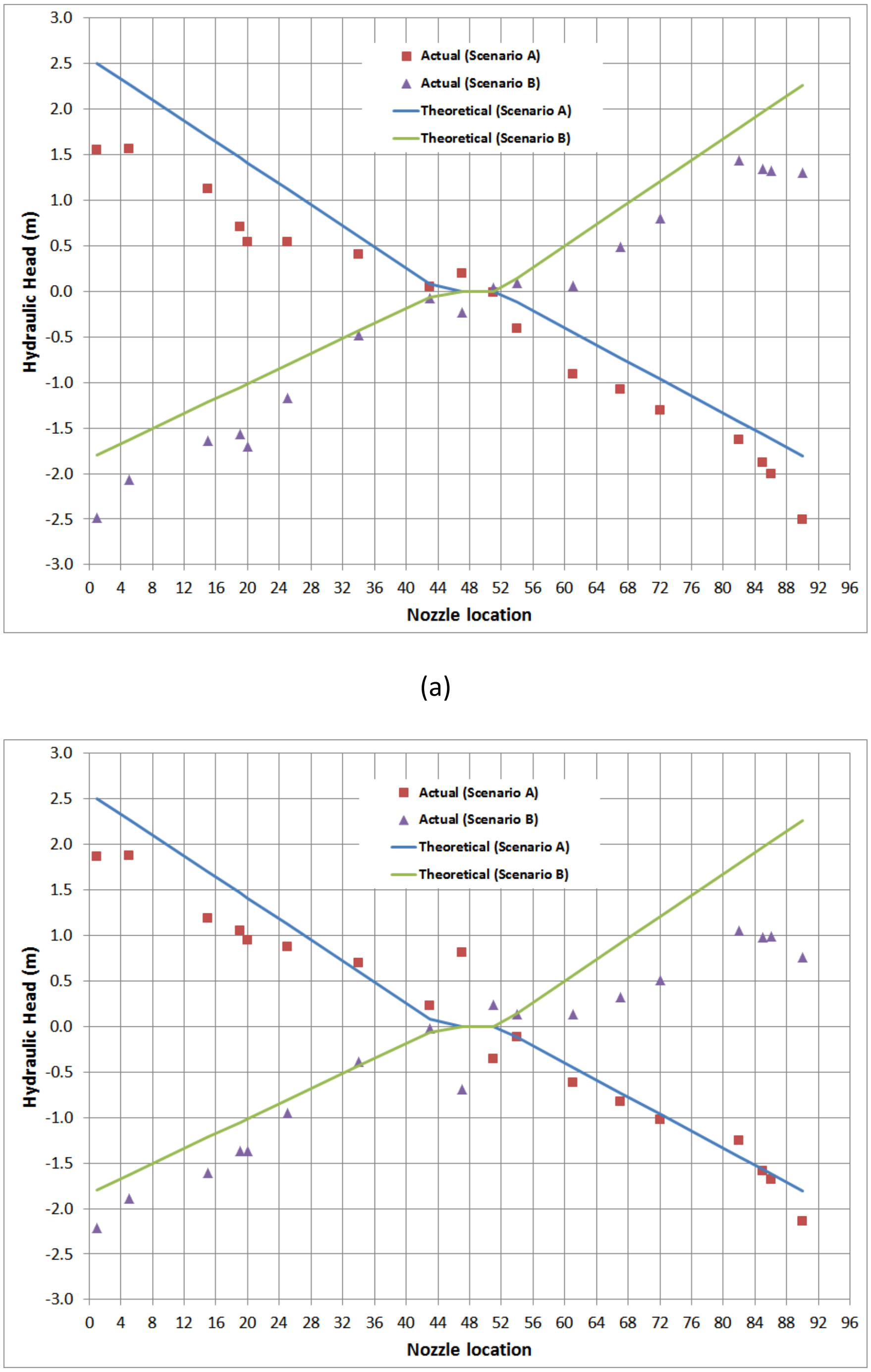


Figure B.3. Initial steady state nozzle pressure for 18 locations along the boom at 310 kPa system pressure.



(a)

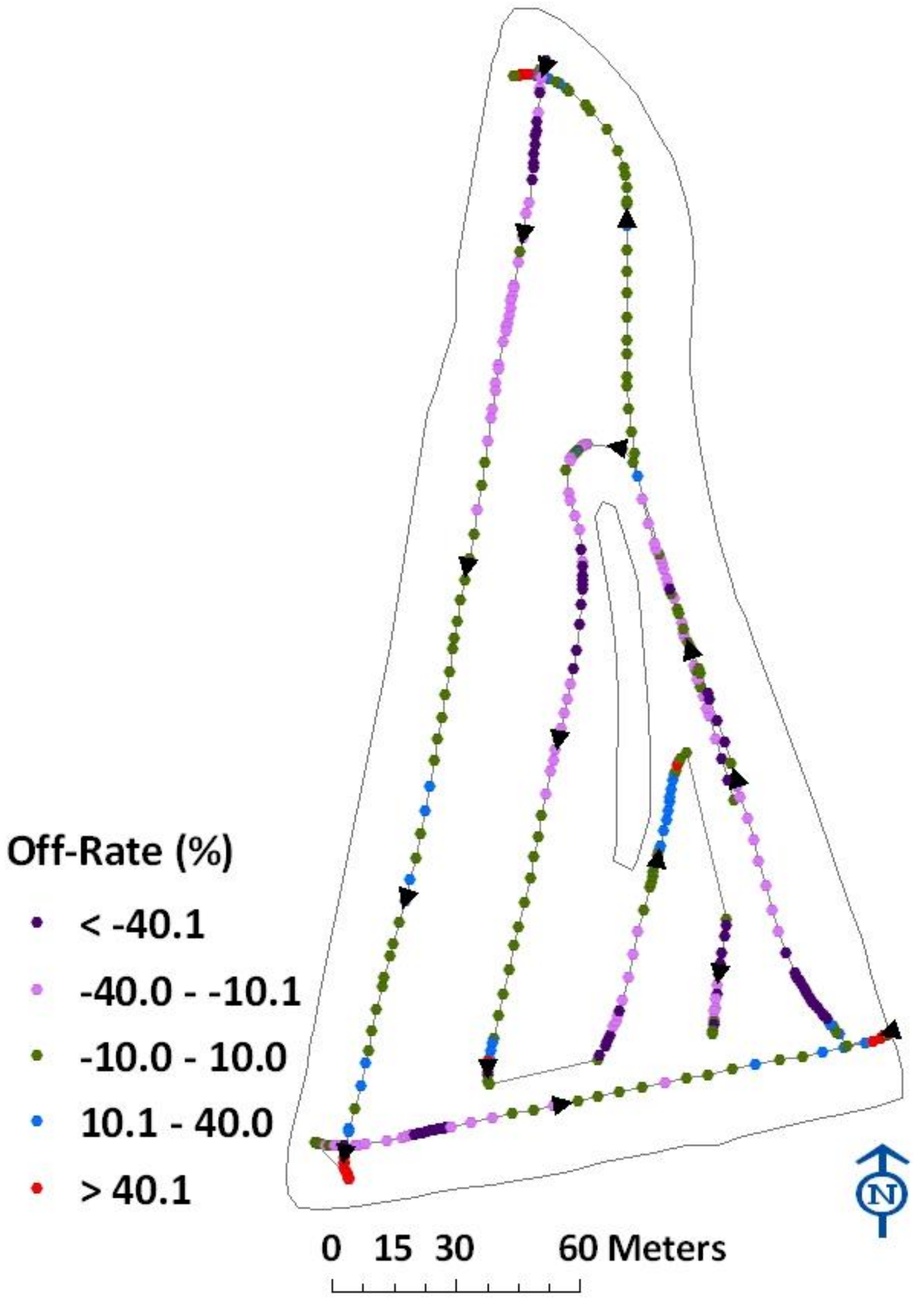
(b)

Figure B.4. An illustration of actual and theoretical hydraulic head during boom-section tilt test at 310 kPa (a) and 161 kPa (b) system pressure. In Scenario A, the left boom-section was lowered and right boom-section was raised and with the opposite for Scenario B.

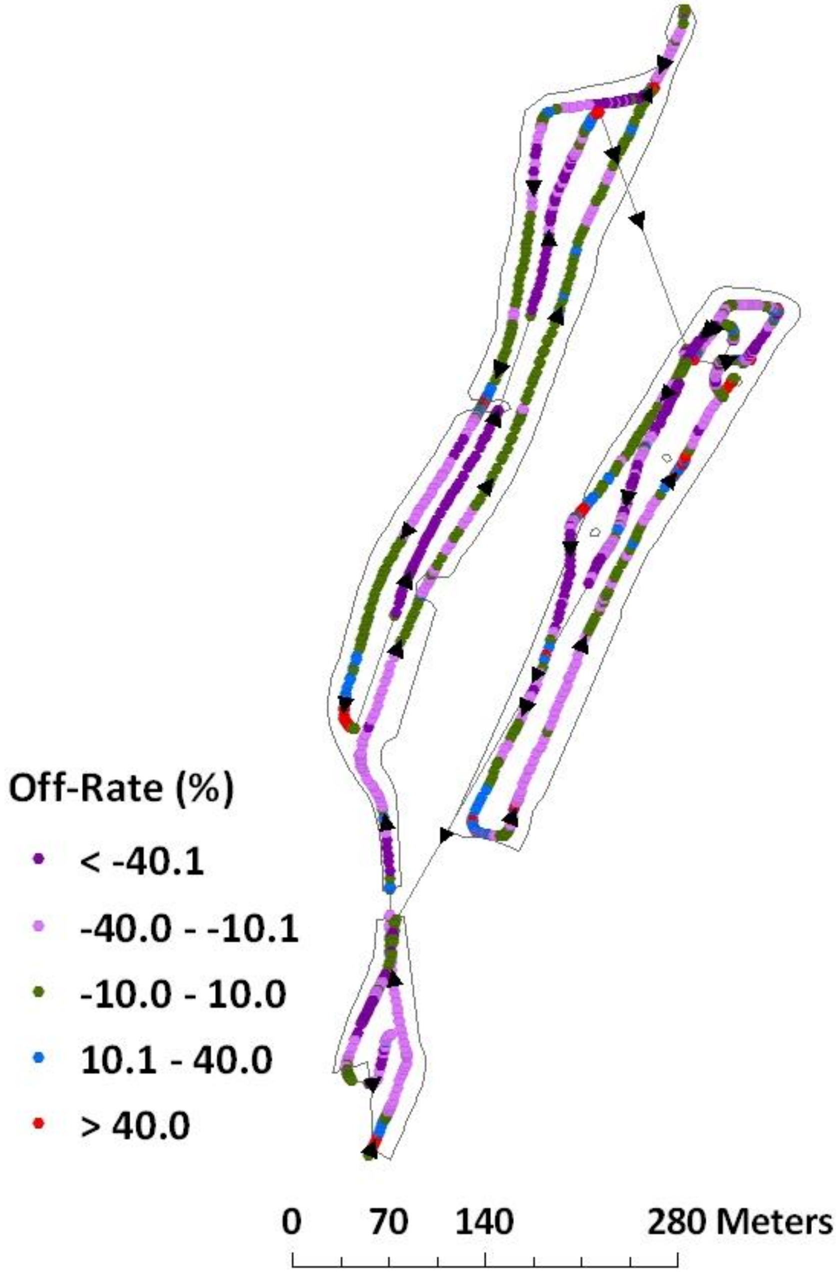
APPENDIX C

ADDITIONAL SPRAYER PERFORMANCE RESULTS

C.1 Nozzle Off-Rate Application Map for Field-1 when using auto-nozzle sprayer with direction of travel indicated by black asrrows, dring field operation.



C.2 Nozzle Off-Rate Application Map for Field-4 when using auto-nozzle sprayer with direction of travel indicated by black asrrows, dring field operation.



C.3 OVERALL MEAN NOZZLE FLOW AND OFF-RATE ERROR FOR AUTO-BOOM SPRAYER WHEN TURNING BOOM-SECTIONS SEQUENTIALLY OFF AND ON AT 5-SECOND INTERVALS.

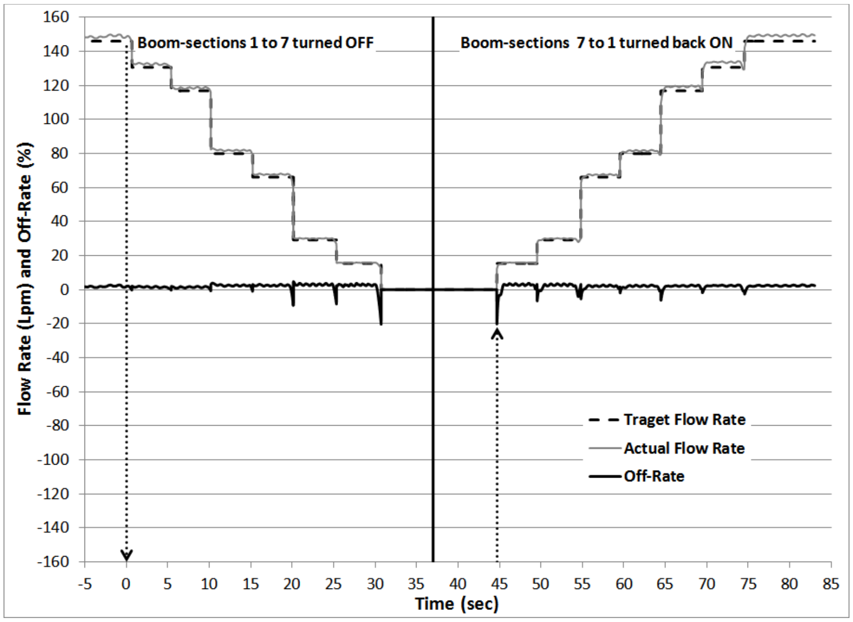


Figure C.1. The target pressure was set at 570 kPa and ground speed at 19.3 kph equivalent to a 124.4 L/ha target rate or 146.0 Lpm system flow.

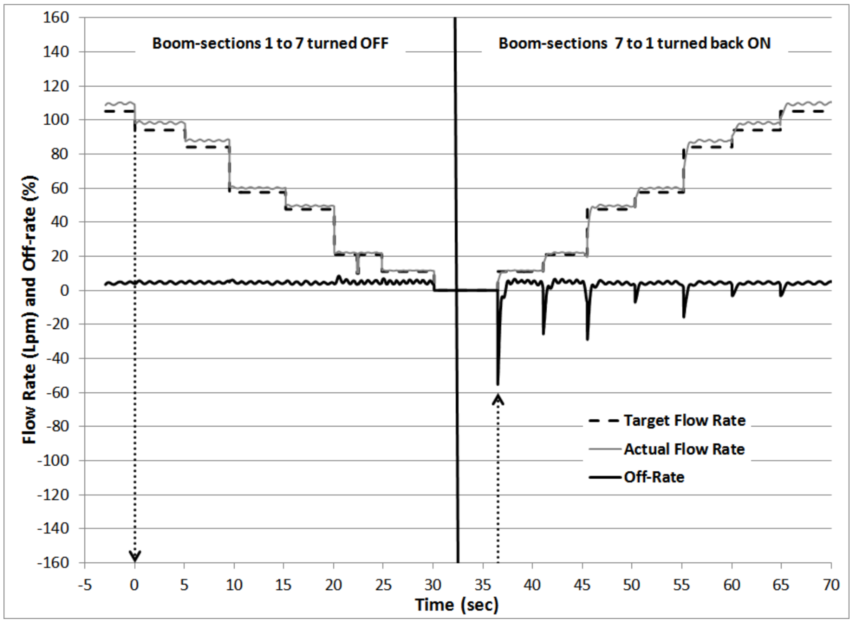


Figure C.2. The target pressure was set at 305 kPa and ground speed at 19.3 kph equivalent to a 94.5 L/ha target rate or 105.1 Lpm system flow.

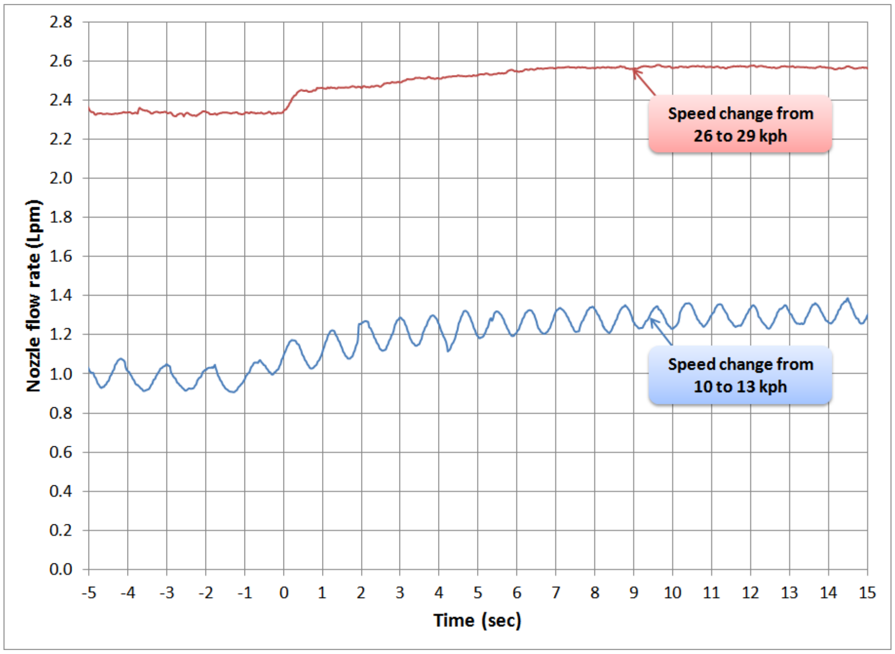


Figure C.3. Tip flow rate response during speed changes for auto-nozzle sprayer (Appendix C.12).

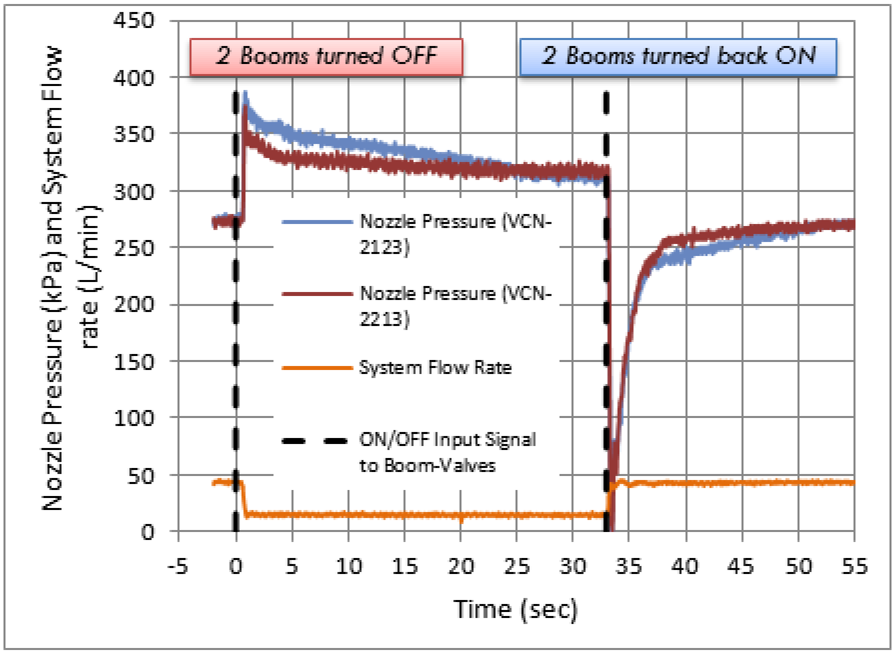


Figure C.4. Nozzle pressure and system flow response when selecting two different valve calibration numbers for butterfly regulating valve.

APPENDIX D

EXPERIMENTAL EQUIPMENT SPECIFICATIONS

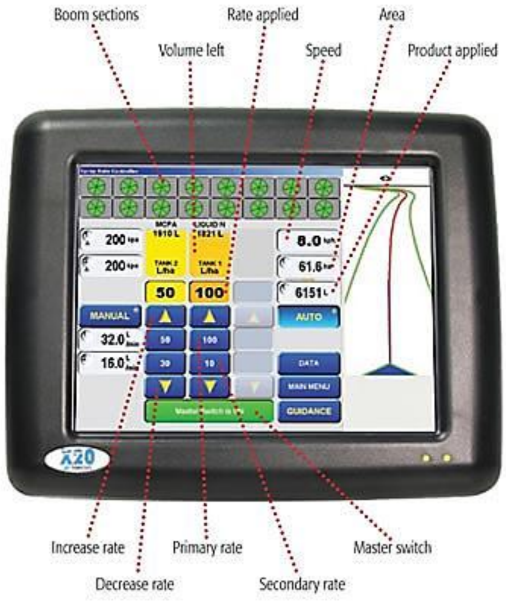
D.1 JOHN DEERE MODEL 6420 TRACTOR

Tractor Power:	
PTO rated, kW:	70.3
Engine:	
Manufacturer:	John Deere
Fuel:	Diesel
Aspiration:	Turbocharger with Intercooler
Cylinders:	4
Displacement, L:	4.5
Rated Engine Speed, RPM:	2300
Cooling:	Liquid
Oil Capacity, L:	15.9
Hydraulic Flow Rate, LPM:	96
Transmission:	
Type:	Infinitely Variable Transmission
Mechanical:	
MFWD:	Yes
Dimensions:	
Wheelbase, mm:	2400
Electrical:	
Display	GreenStar 2

D.2 TRACTOR MOUNTED THREE-POINT HITCH MOUNTED SCHABEN SPRAYER

Manufacturer:	Schaben
Model:	Pro 500 3PT Elliptical
Spray Tank, L (gal):	1893 (500)
Boom type:	Hydraulic Fold X-Boom
Hitch:	3-point
Boom setup	Dry boom
Boom size, m (ft):	18.3 (60)
Number of boom section:	3
Nozzle spacing, cm:	51
Number of nozzles:	25
Nozzle type:	Teejet TT11003 VP
Nozzle solenoid:	Capstan Ag Systems
Flow meter:	Raven
Regulating valve:	Raven
Boom valves:	Raven 2-way boom valve
Pump:	ACE Pumps Corp., Model No. FMC-150-HYD-206

D.3 TOPCON X20 FIELD COMPUTER



Console:	
Manufacturer:	Topcon
Processor:	1 GHz
Memory:	512Mb
Operating system:	Windows XP Pro SP2
Display size, mm (in):	213 (8.4)
Solid State drive, GB:	4
Mounting bracket:	RAM mount
USB ports:	4, USB 2.0
Serial RS232 ports:	4
PS2 ports:	2
VGA ports:	1
10/100 Base T ethernet port:	1
Input voltage, Vdc:	9-18
Control section:	30
Software version:	4.44.0003aS Dec 2, 2005
Pressure Monitoring Software:	
Manufacturer:	Campbell Scientific
Software:	Loggernet 3.4.1
Capabilities:	Datalogger Programming Real-time sensor monitoring

D.4 RAVEN VIPER-II FIELD COMPUTER

Console:

Manufacturer:	Raven
Software version:	2.08F
Microprocessor, MHz:	800
Memory, Mb:	256
Operating system:	Windows XP
Display size, mm (in):	26.4 (10.4), diagonal
Mounting bracket:	RAM mount
USB ports:	3, USB 2.0
Serial RS232 ports:	3

D.5 RAVEN RFM 60P FLOW METER

Manufacturer:	Raven Industries
Model:	063-0171-793 (RFM 60P)
Material:	Polypropylene Body
Inlet, mm (in):	38.1 (1.5)
Outlet, mm (in):	38.1 (1.5)
Pressure rating, kPa (psi):	1206 (175)
TYP pulses/liter (gallon):	19 (72)
Supply voltage, Vdc:	5
Supply current, mA:	10

D.6 RAVEN ¾” POLY BUTTERFLY FLOW REGULATING VALVE

Manufacturer:	Raven Industries
Model:	063-0171-120
Material:	Polypropylene Body
Inlet, mm (in):	19.1 (0.75)
Outlet, mm (in):	19.1 (0.75)
Operating pressure, kPa (psi):	1379 (200)
Supply voltage, Vdc:	12
Supply current, mA:	60
Open/close time, s:	7

D.7 RAVEN ¾” FAST BALL REGULATING VALVE

Manufacturer:	Raven Industries
Model:	063-0172-265
Material:	Stainless steel
Seals	Teflon
Inlet, mm (in):	19.1 (0.75)
Outlet, mm (in):	19.1 (0.75)
Operating pressure, kPa (psi):	1379 (200)
Operating voltage, Vdc:	15
Operating current, A:	3
Open/close time, s:	1.5

D.8 RAVEN 2-WAY BOOM VALVE

Manufacturer:	Raven
Model:	1-063-0172-330
Inlet, cm (in):	5.08 (2), banjo flange
Outlet, cm (in):	2.54 (1), banjo flange
Gallon per minute rating:	40 at 34 kPa (5 psi) pressure drop
Open/close time, s:	≤0.75
Maximum current draw, A:	5
Maximum working pressure, Kpa (psi):	1207 (175)
Close time, s:	0.7

D.9 TEEJET 3-WAY BOOM VALVE WITH METERED BYPASS

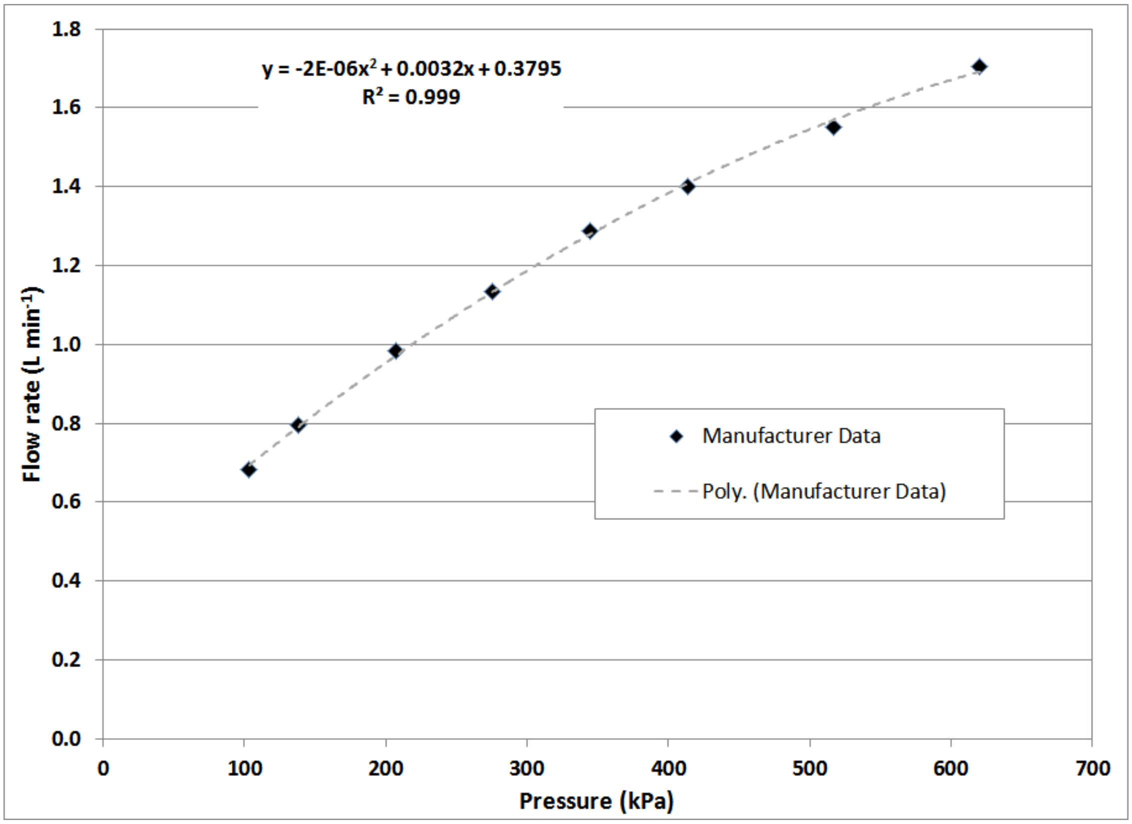
Manufacturer:	Teejet
Model:	DS-430EC
Flow rate, L min^{-1} (gpm):	44.2 (11.7) at 34.4 kPa pressure drop
Max pressure, kPa (psi):	1482 (215)
Current draw, A:	< 0.5 at 12 Vdc
Response time, s:	0.6

D.10 CAPSTAN AG SYSTEMS, INC., SOLENOID VALVES

Voltage rating, Vdc:	12
Pressure rating, kPa (psi):	1034 (150)
Current rating, A:	0.58
ON/OFF Time, ms:	< 150

D.11 PRESSURE VERSUS FLOW CALIBRATION CURVE FOR TT11003 VP NOZZLES

The calibration curve and polynomial fit (Poly.) was attained using manufacturers data (Teejet Catalog 50A, 2008)

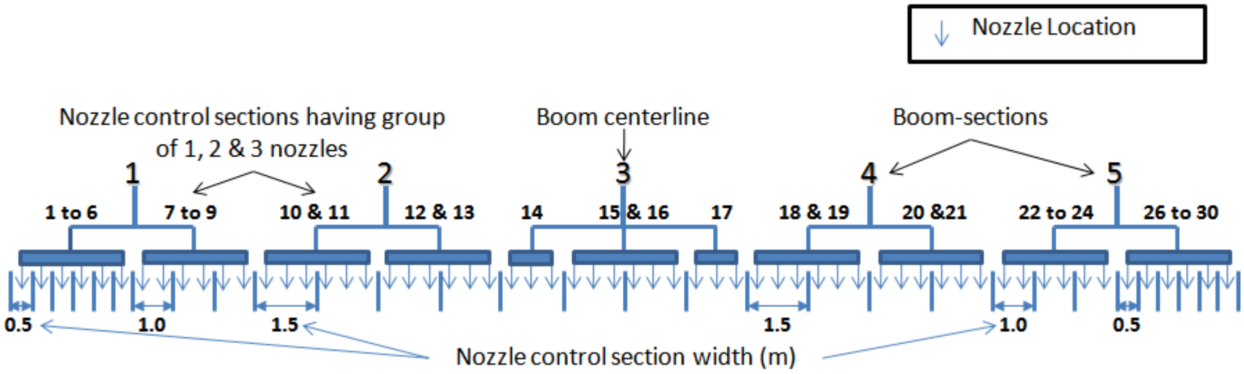


D.12 AG-CHEM ROGATOR 1074 SELF-PROPELLED SPRAYER

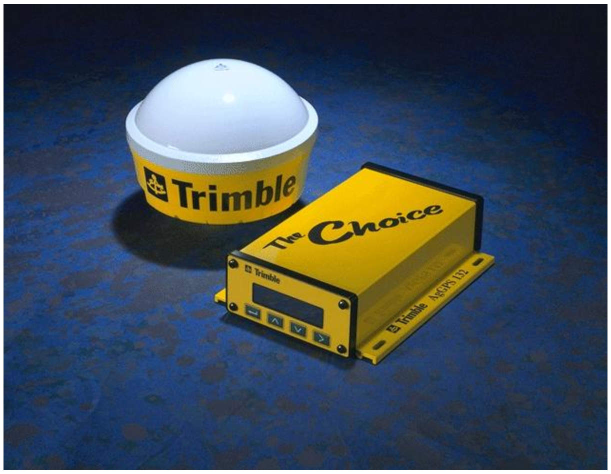
Engine:	
Manufacturer:	Caterpillar
Fuel:	Diesel
Aspiration:	Turbocharger
Displacement, L:	7.2
Cooling:	Air
Sprayer:	
Tank, L:	3785, stainless steel
Pump:	AG-Chem
Pump speed control:	Proportional hydraulic control valve
Dimensions:	
Boom Width, m:	30.4
Boom Height, cm:	78.74 – 210.82, adjustable
Track Width, cm:	305 - 386, adjustable
Ground Clearance, cm:	121.9
Boom setup:	
Number of boom-sections	5
Boom type:	Wet boom using poly tubes
Type of nozzles:	Teejet TT11005 VP, Teejet XR8005 VS
Nozzle spacing, cm:	51
Number of nozzles:	60
Control System:	
Controller:	Topcon X20, Zynx spray rate controller (Version-1.98.1)
Software version:	4.45.0093 Beta S
Spray ECU:	ECU 30S (Firmware version-209)
Spray control section:	30 sections
Flow meter:	AG-Chem
Boom valves:	AGCO, AG-Chem
GPS guidance:	Trimble AG 132 reciever

D.13 CONTROL SECTIONS LAYOUT OF AG-CHEM ROGATOR SS 1074 SPRAYER

The spray boom contained 30 individual nozzle-sections having different section widths



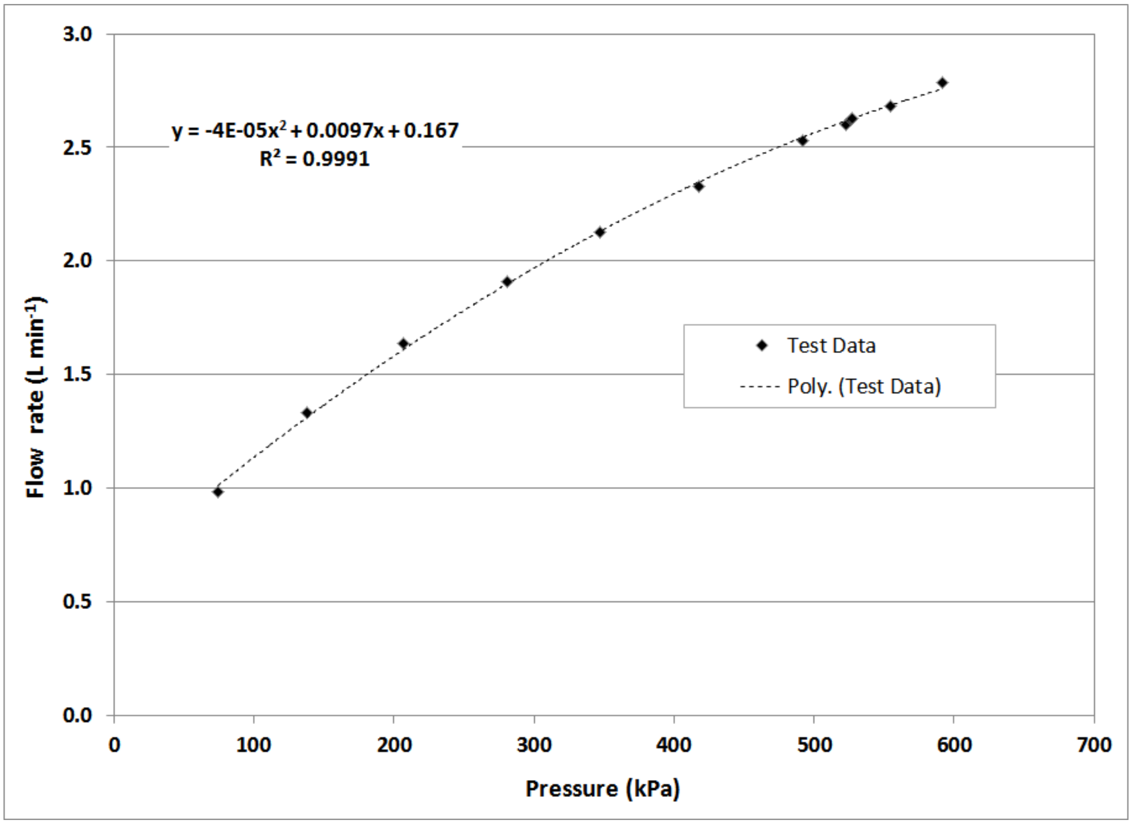
D.14 TRIMBLE AG132 GPS RECEIVER



Manufacturer:	Trimble
Software:	MagMap 96 Utility Software
Receiver:	Integrated 12 channel
Reference station:	Built-in virtual reference station (VRS)
Differential speed accuracy, km h^{-1}:	0.16
Position accuracy:	< 1m RMS horizontal, with sufficient satellites
Differential correction:	Wide Area Augmentation System (WAAS)
Time to first fix, s:	< 30, typically
Update rate, Hz:	1 to 10 Hz

D.15 PRESSURE VERSUS FLOW CALIBRATION CURVE FOR TT11005 NOZZLES

Fifteen tips from location of transducers on the Ag-Chem Rogator sprayer were calibrated on a test table in the laboratory to obtain the calibration curve and polynomial fit for nozzles.

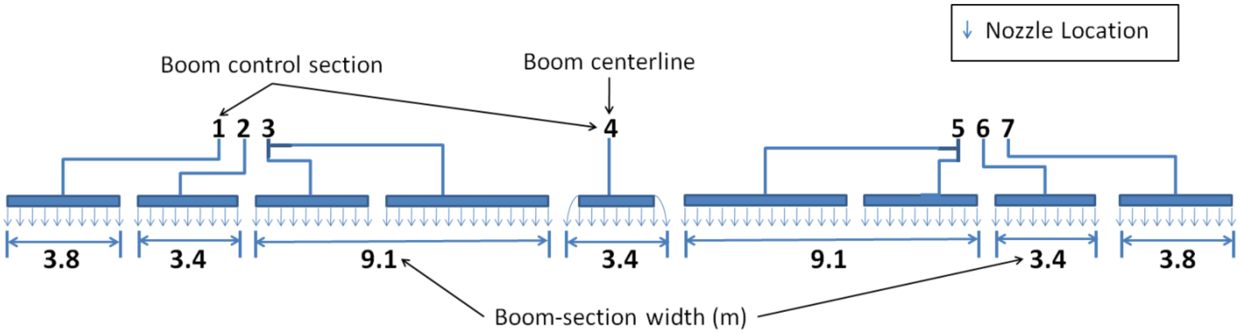


D.16 JOHN DEERE 4930 SELF-PROPELLED SPRAYER

Engine:	
Manufacturer:	John Deere
Fuel:	Diesel
Aspiration:	Turbocharger
Displacement, L:	9
Sprayer:	
Tank, L:	4542, stainless steel
Pump:	Hypro (hydraulically controlled)
Rate Control:	John Deere Spray Star
Dimensions:	
Boom Width, m:	36.5
Boom Height, cm:	61 – 231, adjustable
Breakaway Width, m:	4 tip, full boom standard
Wheelbase, cm:	432
Ground Clearance, cm	127
Boom Setup:	
Boom Sections:	7
Boom type:	Wet boom
Type of nozzles:	Teejet AI11003 VS
Nozzle spacing, cm:	38
Number of nozzles:	95
Control System:	
Controller (software Part No. and version):	John Deere SprayStar (N307154 and 06.14)
Display-1 (software Part No. and version):	GreenStar 2 (RF500027 and 02.03)
Display-2	Original GreenStar display
Spray control section:	7
Flow meter, mm (in):	38.1 (1.5), optional 2nd for high flow system
Boom valves:	John Deere Spray Master
GPS guidance:	Trimble RTK receiver with R8 Rover and R7 Base

D.17 CONTROL SECTIONS LAYOUT OF JOHN DEERE 4930

The sprayer contained seven individual boom-sections having different section widths



D.18 GNSS RTK RECEIVER – R8 ROVER

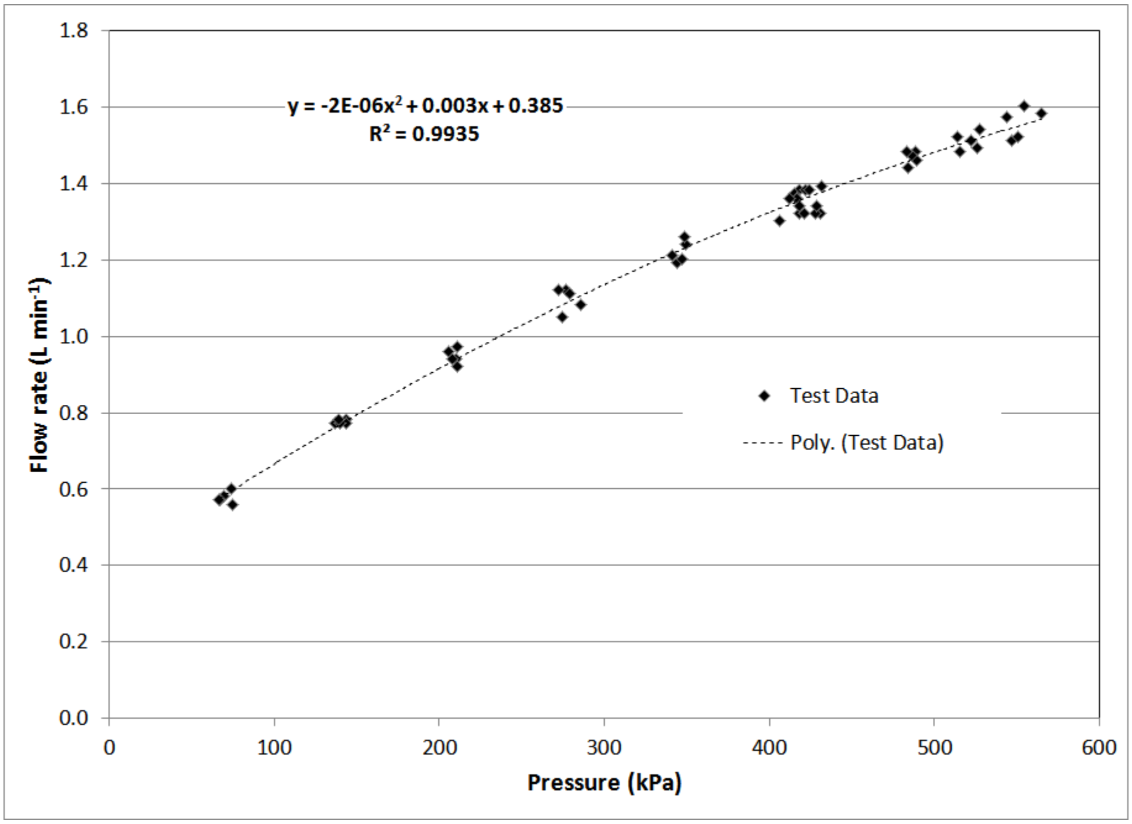
Code differential GNSS positioning:	Horizontal….0.25 m + 1 ppm RMS
	Vertical………0.50 m + 1 ppm RMS
	WAAS accuracy typically…<5 m 3DRMS
Static and Fast-Static GNSS surveying:	Horizontal….3 mm + 0.1 ppm RMS
	Vertical………3.5 mm + 0.1 ppm RMS
Kinematic surveying:	Horizontal….10 mm + 1 ppm RMS
	Vertical………20 mm + 1 ppm RMS
	Initialization time typically…<10 seconds
	Initialization reliability typically….99.9%
Data Storage, Mb:	57 internal memory
NEMA output:	GPGGA, GPVTG
Update rate, Hz:	5

D.19 GNSS RTK RECEIVER R7 BASE

Code differential GNSS positioning:	Horizontal….0.25 m + 1 ppm RMS
	Vertical………0.50 m + 1 ppm RMS
	WAAS accuracy typically…<5 m 3DRMS
Static and FastStatic GNSS surveying:	Horizontal….3 mm + 0.1 ppm RMS
	Vertical………3.5 mm + 0.1 ppm RMS
Kinematic surveying:	Horizontal….10 mm + 1 ppm RMS
	Vertical………20 mm + 1 ppm RMS
	Initialization time typically…<10 seconds
	Initialization reliability typically….99.9%
Power ports:	2 external
Battery ports:	2 internal
Serial ports:	3
NMEA outputs:	16

D.20 PRESSURE VERSUS FLOW CALIBRATION CURVE FOR AI11003 VS NOZZLES

Five tips from location of pressure transducers location on the John Deere sprayer were calibrated on a test table in the laboratory to obtain the calibration curve and polynomial fit (Poly.)



APPENDIX D

INSTRUMENTATION AND DATA ACQUISITION

D.1 MEASUREMENT COMPUTING USB-4303FS.

Counter Configuration:	Two 9513 devices, 5 up/down counters, 16 bits each
Counter Compatibility, V/TTL:	5
Digital Input:	8
Digital Output:	8
Memory, bytes:	256 (EEPROM)
USB:	USB 2.0

D.2 COMPACT RIO-9014 CONTROLLER.

Manufacturer:	National Instruments
Part:	779564-01
Operating system:	Real-Time
Processor core type:	PowerPC
CPU clock frequency, MHz:	400
Memory, Mb:	128
Ethernet ports:	1
Ethernet port type:	10BaseT, 100BaseT
Serial RS232 port:	1
USB ports:	Yes

D.3 COMPACTRIO-9103 CHASSIS.

Manufacturer :	National Instrument
Form Factor :	CompactRIO
Part Number :	779053-01
Operating System/Target :	Real-Time
Reconfigurable FPGA:	
FPGA :	Virtex-II
Chassis:	
Number of Slots :	4
Power Consumption, W:	3
Minimum Operating Temperature, °C :	-40
Maximum Operating Temperature, °C:	70

D.4 NATIONAL INSTRUMENT 9221 C SERIES ANALOG MODULE.

Manufacturer :	National Instrument
Form Factor :	CompactDAQ , CompactRIO
Part Number :	779014-01
Operating System/Target:	Real-Time , Windows
Measurement Type :	Voltage
Isolation Type :	Ch-Earth Ground Isolation
Analog Input	
Channels :	0 , 8
Single-Ended Channels:	8
Resolution, bits :	12
Sample Rate, kS/s:	800
Max Voltage, V:	60
Maximum Voltage Range, V:	-60, 60
Maximum Voltage Range Accuracy, V:	0.069

D.5 NATIONAL INSTRUMENT 9476 C SERIES DIGITAL OUTPUT MODULE.

Manufacturer :	National Instrument
Form Factor:	CompactDAQ , CompactRIO
Part Number:	779140-01
Operating System/Target:	Real-Time , Windows
Measurement Type :	Digital
Isolation Type:	Ch-Earth Ground Isolation
Digital I/O	
Bidirectional Channels:	0
Input-Only Channels :	0
Output-Only Channels:	32
Number of Channels:	0 , 32
Timing:	Software
Max Clock Rate, kHz:	2
Output Current Flow:	Sourcing
Current Drive Single, A:	0.25
Supports Handshaking I/O:	No
Supports Pattern I/O :	Yes
Maximum Output Range, V:	6, 36

D.6 National instrument NI 9870 4-port RS232 CompactRIO Serial Interface Module.

Manufacturer :	National Instrument
Product Family:	Serial
Form Factor:	CompactRIO
Part Number:	779891-02 , 779891-01
Operating System/Target:	FPGA
LabVIEW RT Support:	No
Voltage, Vrms:	5
Current, A:	0.1
Source :	Additional Power Required
Isolation Type:	Bank Isolation
Serial Standard Compatibility:	RS-232
Port Information	
Number of Ports:	4
I/O FIFO Buffer Size:	64 B
Max Device Connections / Port:	1

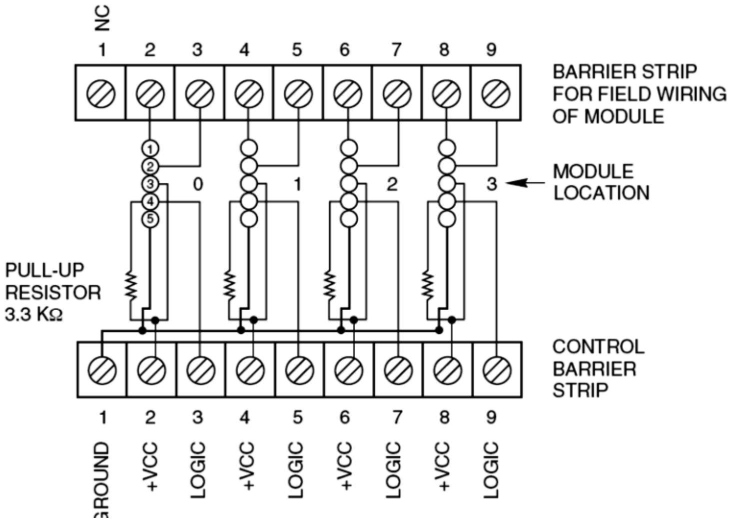
D.7 NATIONAL INSTRUMENT C SERIES 9403 DIGITAL INPUT MODULE.

Manufacturer:	National Instrument
Form Factor:	CompactDAQ , CompactRIO
Part Number:	779787-01
Operating System/Target:	Real-Time , Windows
Measurement Type:	Digital
Isolation Type:	Ch-Earth Ground Isolation
Product Family:	Serial
Form Factor:	CompactRIO
Operating System/Target:	FPGA
Analog Output	
Bidirectional Channels:	32
Timing:	Hardware
Max Clock Rate, MHz:	10
Logic Levels:	TTL
Maximum Input Range, V:	0, 5.25
Maximum Output Range, V:	0 , 5.25

D.8 GRAYHILL INC. DC OUTPUT MODULES.

Manufacturer	Grayhill Inc.
Part number	70G ODC15
Maximum Line Voltage, Vdc:	60
Load Voltage Range, Vdc:	3-60
Max. Off-State Leakage @ Max. Line, mA:	1.5
Maximum Turn-On Time, µSec:	20
Maximum Turn-Off Time, µSec:	50
Typ. Power Dissipation, W/A:	1
Clamping Voltage, Vdc:	80
Nominal Logic Voltage (Vcc), Vdc:	15
Logic Voltage Range, Vdc:	10-20
Maximum Logic Supply Current @ Nominal Vcc, mA:	9
Nominal Input Resistance (Rx), Ω:	1500
Minimum Drop Out Voltage, Vdc:	1

D.9 GRAYHILL 70GRCK4R 4 POSITIVE OR NEGATIVE TRUE LOGIC RACKS FOR 70G ODC15 OUTPUT MODULES.



Schematics for the **70GRCK4R** rack.

D.10 PCB PIEZOTRONICS INC. THIN FILM PRESSURE TRANSDUCER.

Manufacturer:	PCB Peizotronics
Part number:	1502B81EZ100psiG
Measurement range, kPa (psi g):	0-690 (0-100)
Output, (Vdc):	0-10
Accuracy:	≤ 0.25% FS
Drift:	≤ 0.2 % FS/Year
Sensitivity, mV/kPa (mV/psi):	14.5 (100)
Resolution:	≤ 0.01 % FS
Response time, ms:	≤ 1
Environment:	
Proof pressure:	2X FS
Burst Pressure:	> 35X FS
Fatigue life:	108 FS cycles
Electrical:	
Supply voltage, VDC:	11.5 to 30
Current consumption, mA:	6
Physical:	
Pressure port:	1/4-18 NPT
Thread:	External

D.11 FLOW TECHNOLOGY FLOW METER WITH PICKUP.

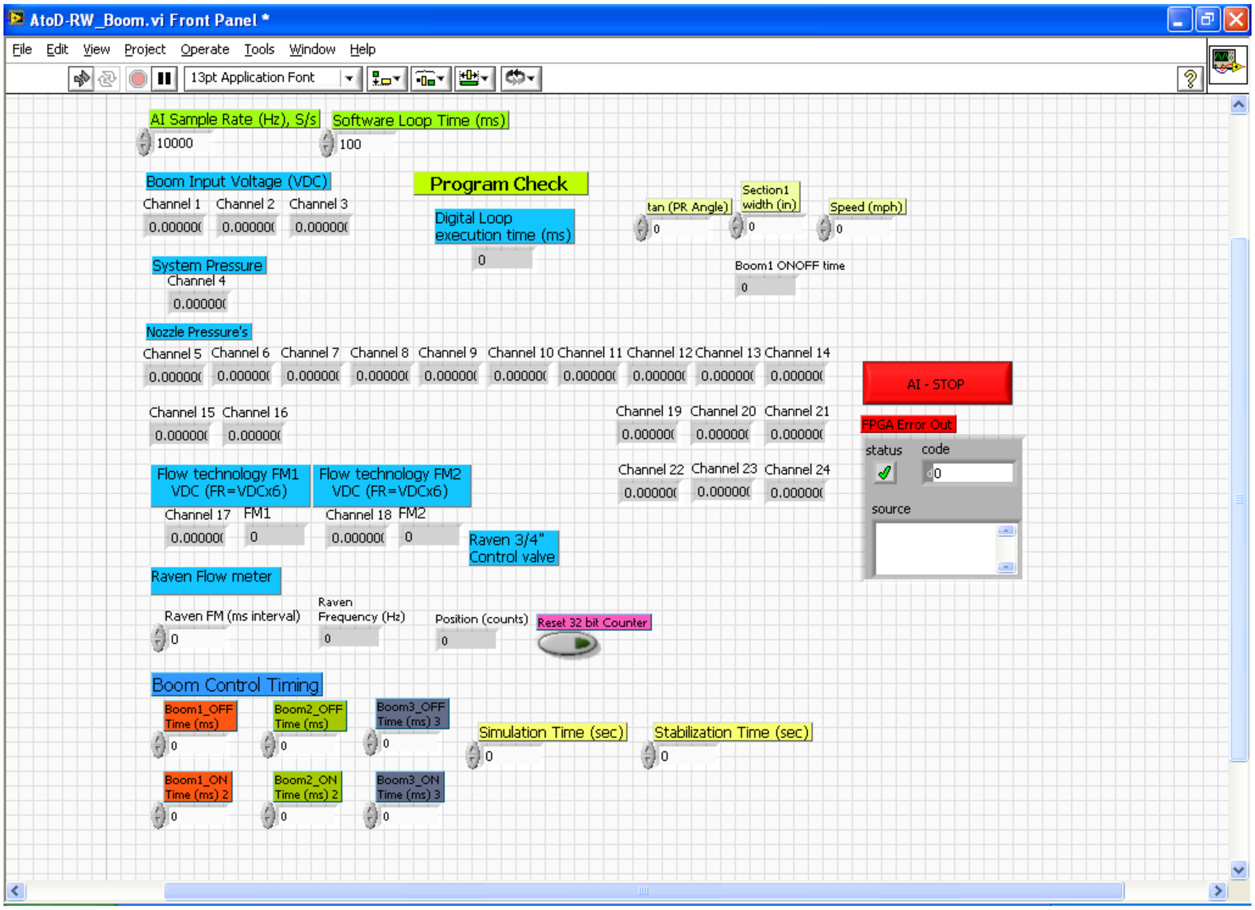
Manufacturer:	Flow Technology
Part number:	FT-16 NEXW-LEG-6
Measurement range L min^{-1} GPM	0-227 (0-60)
Output, Vdc:	0-10
Accuracy:	±0.05% of reading
Repeatability:	±0.05% of reading
Linearity:	±0.10% of linearing electronic
Rotor material:	Ceramic
Response time, ms:	3-4
Electronic pickup	
Part number:	LN-5-C-V1-9
Applied voltage In, VDC:	10-36
Power consumption, mW:	300
Input frequency, Hz:	5-3000
Output frequency, Hz:	1-3500
Analog voltage output, Vdc:	1-10
Linearizer latency, ms:	10
Analog voltage output accuracy:	0.1% of full scale
Linearization method:	High density linear interpolatd frequency mapping

APPENDIX E

EXAMPLE PROGRAMS AND SCREENSHOTS

E.1 FRONT PANEL SCREENSHOT OF A LABVIEW FPGA PROGRAM FOR AUTO-BOOM CONTROL TESTS.

The program read and writes to analog, digital input or digital output modules during simulated tests



AI Sample Rate (Hz), S/s 10000
Software Loop Time (ms) 100

Boom Input Voltage (VDC)
Channel 1 0.00000(
Channel 2 0.00000(
Channel 3 0.00000(

Digital Loop execution time (ms) 0

tan (PR Angle) 0
Section1 width (in) 0
Speed (mph) 0
Boom1 ONOFF time 0

System Pressure
Channel 4 0.00000(

Nozzle Pressure's
Channel 5 0.00000(
Channel 6 0.00000(
Channel 7 0.00000(
Channel 8 0.00000(
Channel 9 0.00000(
Channel 10 0.00000(
Channel 11 0.00000(
Channel 12 0.00000(
Channel 13 0.00000(
Channel 14 0.00000(
Channel 15 0.00000(
Channel 16 0.00000(
Channel 19 0.00000(
Channel 20 0.00000(
Channel 21 0.00000(
Channel 22 0.00000(
Channel 23 0.00000(
Channel 24 0.00000(

FPGA Error Out
status ✓
code 0
source

Flow technology FM1 VDC (FR=VDCx6)
Channel 17 0.00000(
FM1 0

Flow technology FM2 VDC (FR=VDCx6)
Channel 18 0.00000(
FM2 0

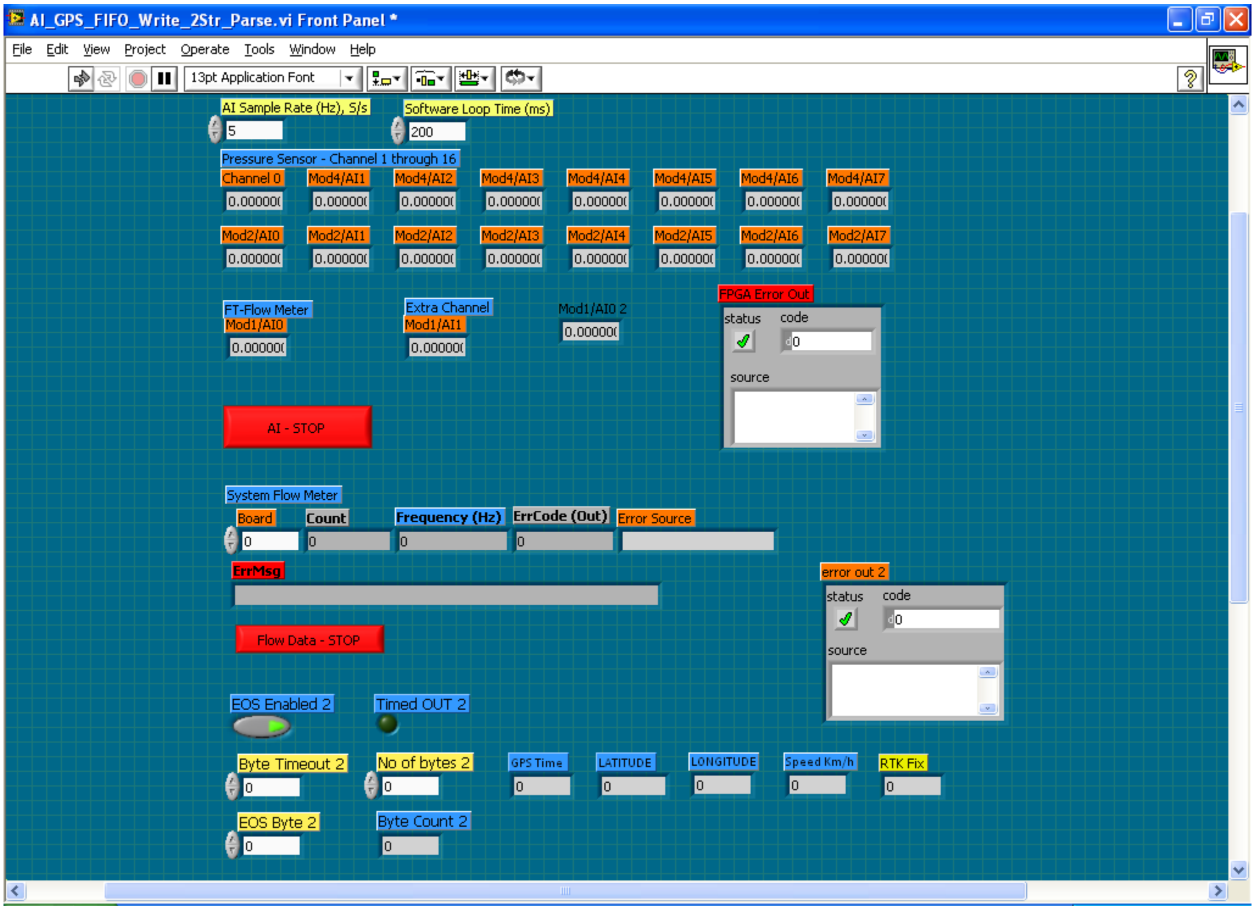
Raven 3/4" Control valve

Raven Flow meter
Raven FM (ms interval) 0
Raven Frequency (Hz) 0
Position (counts) 0

Boom1_OFF Time (ms) 0
Boom2_OFF Time (ms) 0
Boom3_OFF Time (ms) 3 0
Boom1_ON Time (ms) 2 0
Boom2_ON Time (ms) 2 0
Boom3_ON Time (ms) 3 0
Simulation Time (sec) 0
Stabilization Time (sec) 0

E.2 FRONT PANEL SCREENSHOT OF A FPGA PROGRAM DURING FIELD TESTS.

The program read and writes to analog, digital input, digital output and serial modules



AI Sample Rate (Hz), S/s 5

Software Loop Time (ms) 200

Pressure Sensor - Channel 1 through 16

Channel 0	Mod4/AI1	Mod4/AI2	Mod4/AI3	Mod4/AI4	Mod4/AI5	Mod4/AI6	Mod4/AI7
0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Mod2/AI0	**Mod2/AI1**	**Mod2/AI2**	**Mod2/AI3**	**Mod2/AI4**	**Mod2/AI5**	**Mod2/AI6**	**Mod2/AI7**
0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

FT-Flow Meter Mod1/AI0 0.000000

Extra Channel Mod1/AI1 0.000000

Mod1/AI0 2 0.000000

FPGA Error Out
status ✓ code 0
source

System Flow Meter

Board	Count	Frequency (Hz)	ErrCode (Out)	Error Source
0	0	0	0	

ErrMsg

error out 2
status ✓ code 0
source

EOS Enabled 2

Timed OUT 2

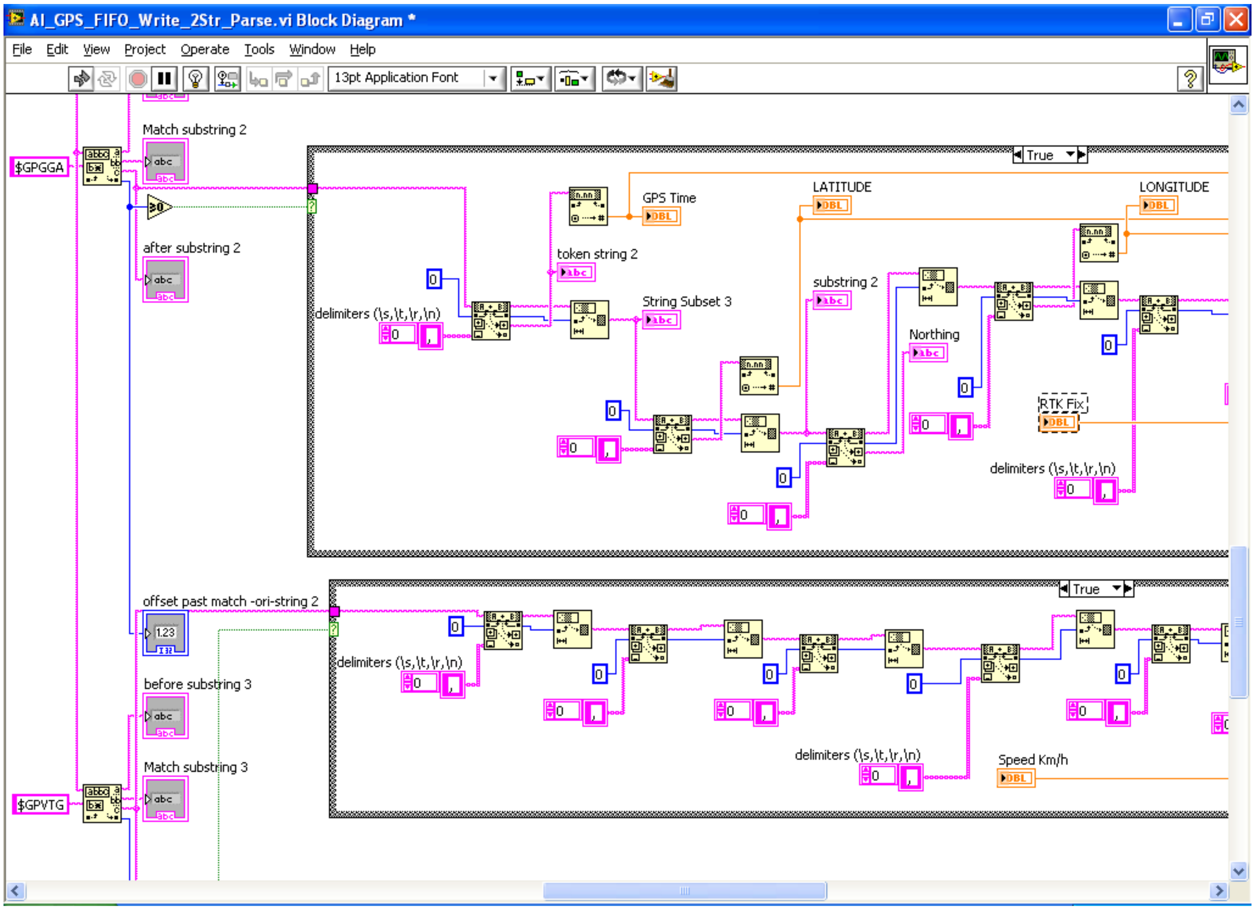
Byte Timeout 2	No of bytes 2	GPS Time	LATITUDE	LONGITUDE	Speed Km/h	RTK Fix
0	0	0	0	0	0	0

EOS Byte 2 0

Byte Count 2 0

E.3 BLOCK DIAGRAM SCREENSHOT OF A FPGA PROGRAM DURING FIELD TESTS

This part of the program read, parse and write GPS data



E.4 EXAMPLE MATLAB PROGRAM TO ANALYZE NOZZLE PRESSURE PARAMETERS .

This program did analyses of nozzle pressure data when boom valves control were turned OFF during different tests

```
clear all;clc;close all;format long
% parameters;
%% ----------------------
Time=xlsread('AB_10_anal_OR.xlsx','70_10_r3','E370:E514');
BoomVolt=xlsread('AB_10_anal_OR.xlsx','70_10_r3','F370:H514');
Parameter=xlsread('AB_10_anal_OR.xlsx','70_10_r3','BQ370:BR514');
Ni=10;Nf=134;
%% ----------------------
% % Calculate boom valve shut Off Time and write on an excel sheet
%%  ------------
[nrow ncol]=size(BoomVolt)
for j=1:ncol
   Btime=-1;
   for i=1:nrow
      if ((BoomVolt(i,j)<10) && (Btime==-1))
         Btime = Time (i);
      else
         BOT(j,1) = 0;
      end
      BOT(j,1) = Btime;
   end
end
xlswrite('AB_2way_summary_pres.xlsx',BOT,'70_10','J38')
clear nrow ncol Btime
%% ----------------------
% % Calculate average initial nozzle pressure, average final pressure, settling time,% overshoot, peak time and
write on an excel sheet
%%  ------------
[nrow,ncol]=size(Parameter);
for k=1:ncol
   ParaIni(k,1)=(mean(Parameter(1:Ni,k)));
   ParaFin(k,1)=(mean(Parameter(Nf:end,k)));
end
for j=1:ncol
   PeakVal = 0;
   TimeIni = -1;
   TimeFi = 0;
   TimeFin = 0;
   Tim = 0;
   Psum = 0;
   Pavg = 0;
   Count = 0;
   check = BOT(2,1); %check for this value based on boom-section number turned OFF/ON
   for i=1:nrow
      if (Parameter(i,j) > PeakVal)
```

```
            PeakVal = Parameter(i,j);
            PeakT = Time(i);
        end
        Change1 = abs(((Parameter(i,j) - ParaIni(j)) * 100) / ParaIni(j));
        Change2 = abs(((Parameter(i,j) - ParaFin(j)) * 100) / ParaFin(j));
        if ((Change1 > 5) && (TimeIni == -1))
            TimeIni = Time(i);
        end
        if (TimeIni < check)
            TimeIni = -1;
        end
        if (i == nrow)
            timend = Time(i);
        end
        if ((Change2 < 5.0) && (TimeFin == 0))
            TimeFin = Time(i);
        elseif (Change2 > 5.0)
            TimeFin = 0.0;
        end
        if (TimeIni == -1)
            TimeFin = 0;
        end

        if (Parameter (i,j) > 5)
            Pin = Parameter (i,j)
            Psum =Psum + Pin
            Count = Count + 1
        end
        if (Count > 0)
            Pavg = Psum/Count
        end

        Sint = TimeFin - TimeIni;
                if (Sint >= 0)
                    STime = Sint;
                elseif (TimeFin == 0)
                    STime = 0;
                end

        OShoot(j,1) = ((PeakVal - ParaFin(j)) * 100) / ParaFin(j);
        peak_Value(j,1)=PeakVal;
        Stime(j,1)=STime;
       % peak_t(j,1)=PeakT;
       % peak_time(j,1)=PeakT - TimeIni;
        ini_time(j,1)=TimeIni;
        fin_time(j,1)=TimeFin;
        P_avge(j,1)= Pavg;
    end

clear STime TimeIni TimeFin PeakVal PeakT Psum Count Pavg
```

```
end
%{
jj=int2str(j);
S=strcat('R',jj)
%}
xlswrite('AB_2way_summary_pres.xlsx',ParaIni,'70_10','B38')
xlswrite('AB_2way_summary_pres.xlsx',ParaFin,'70_10','C38')
xlswrite('AB_2way_summary_pres.xlsx',ini_time,'70_10','D38')
xlswrite('AB_2way_summary_pres.xlsx',fin_time,'70_10','E38')
xlswrite('AB_2way_summary_pres.xlsx',Stime,'70_10','G38')
xlswrite('AB_2way_summary_pres.xlsx',peak_Value,'70_10','H38')
xlswrite('AB_2way_summary_pres.xlsx',P_avge,'70_10','I38')
clear nrow ncol
TimeL=min(ini_time);
lag_time=ini_time-TimeL;
%% ----------------------
% % Calculate system flow rate settling time and write on an excel sheet
%%  ------------
[nrow ncol]=size(Flowrate)
Ftime = 0;
for i=1:nrow
   if ((Flowrate(i) == 0) && (Ftime==0))
       Ftime = Time (i);
   end
end
FST = Ftime
FRS_Time=BOT - FST;
% save st_output OShoot STime TimeIni TimeFin PeakPres PeakT
1
```