Flow Variability of an Aerial Variable-Rate Nozzle at Constant Pressures

D. E. Martin

Abstract. *Variable-rate ground application systems have been in use for the past 15 years, but due to high application speeds, flow requirements, and aerodynamic considerations, variable-rate aerial nozzles have not been available until now. In 2006, Spray Target, Inc. (Rosemount, Minn.) released the VeriRate™ variable-rate aerial nozzle, the first commercially-available retrofit aerial nozzle of its kind. Conventional, fixed-orifice, hydraulic aerial nozzles are physically and practically limited to a doubling of flowrate. This new variable-orifice aerial nozzle promised a 10X rate change. Using a standard aircraft spray boom, this study quantified flowrate and flowrate variability from a set of 48 VeriRate nozzles at spray pressures ranging from 207-483 kPa (30-70 psi). Results indicated a 3.4 fold increase in flowrate change (2.35 to 8.10 L min^{-1}) that could be achieved with this nozzle, but shy of the desired 10X rate change. Additionally, measured flowrate from the nozzles was dependent on the pressure-up sequence. Excess flow variability (CV>25%) between nozzles was found when spray pressure was gradually applied to the nozzles. Initially "spiking" the spray pressure to 483 kPa (70 psi) removed virtually all excess flow variability, except at 207 kPa (30 psi). Aerial applicators will be able to use the results from this study to make informed decisions when selecting variable-rate aerial nozzles.*

Keywords. *Variable rate application, Nozzles, Aerial spraying, Agricultural aviation.*

With the advent of global positioning system (GPS) technologies came the ability to apply pest control products on a site-specific basis. Traditional methods of pesticide application required application of a single rate of product across an entire field or manual spot-spraying for targeted pests. Currently, with open civilian access to GPS positional data, geo-referenced prescription maps can direct a sprayer to spray only where needed or vary the rate of product applied as needed throughout a field. Variable-rate ground application systems have been in use for the past 15 years, but due to high application speeds, flow requirements, and aerodynamic considerations, variable-rate aerial nozzles had not been available until now.

In 2006, Spray Target, Inc. (Rosemount, Minn.) released its newly designed VeriRate™ variable-rate aerial nozzle based on earlier patented research by Womac and Bui (1999, 2002). This retrofit nozzle is important to the aerial application industry because it addresses two main issues inherent when trying to make variable-rate aerial applications with conventional hydraulic nozzles. The first is a change in droplet spectrum that results when changing flowrates via pressure changes with a fixed-orifice nozzle. The VeriRate nozzle has a flexible orifice which increases in diameter with increases in pressure. This allows for an increase in flowrate with increased pressure and may possibly reduce driftable fines at higher pressures compared to a conventional fixed orifice nozzle. However, only the flowrate performance of the nozzle was evaluated for this study. Flowrate from a hydraulic nozzle is adjusted by changing the input pressure to the system. An increase in pressure will result in an increase in flowrate. However, for a fixed-orifice nozzle, this flow is turbulent and follows a quadratic pressure-flow relationship given by the Bernoulli equation for irrotational or inviscid flow fields. Therefore, in order to double the flowrate, the system pressure must be quadrupled. This relationship for agricultural sprayers has been aptly described by Hughes (1985). Using conventional hydraulic nozzles to make variable-rate aerial applications creates a problem because there is a typically a physical maximum pressure limitation of 414 to 552 kPa (60 to 80 psi) on most aerial application systems. On the low end, an applicator has to run at least 138 kPa (20 psi) on the system to properly operate the check valves. So the effective pressure range available to the operator is, for all practical purposes, 138 to 552 kPa (20 to 80 psi). Aside from any potential drift issues, this pressure range would only allow a doubling of flowrate. To be adequately robust, a variable-rate aerial nozzle would need to be capable of producing a 5X rate change or better [i.e., 18.7 to 93.5 L ha^{-1} (2.0 to 10.0 GPA)] with minimal

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The author is **Daniel E. Martin, ASABE Member Engineer,** Agricultural Engineer, United States Department of Agriculture, Agricultural Research Service, College Station, Tex. **Corresponding author:** Daniel E. Martin, 2771 F&B Rd., College Station, TX 77845; phone: 979-260-9290; e-mail: Daniel.Martin@ars.usda.gov.

change in droplet spectra. This range of application rate covers the vast majority of rates commonly used in the aerial application industry.

The VeriRate nozzle was designed to address both of these issues (fig. 1). As pressure to the nozzle is increased, a plastic metering assembly with a rubber diaphragm in the nozzle, which normally presses against the spray orifice, pushes back against a stainless steel spring at the rear of the nozzle to create a larger orifice, allowing more fluid to flow through. The metering assembly controls flow while the spray tip creates the discharge pattern. This variable orifice allows for increased flowrate as pressure is increased. Since flowrate for this nozzle is so dependent on pressure, any inherent differences in the flow characteristics in these nozzles could have a significant impact on overall application rate and spray pattern.

Published flowrate data for aerial nozzles are sparse. However, it is typically accepted that the flowrate variability within a set of nozzles should be less than 10% (*ASABE Standards*, 2007). Smith (1992) conducted a drift study with conventional flat fan nozzles and tested the nozzles for flowrate prior to the study, but just excluded from the study any nozzles that resulted in flowrate variability greater than 5%. Determination of flowrate variability in these newly designed variable-rate aerial nozzles is important because excess variability in either flowrate or droplet size from nozzles can lead to poor coverage, reduced efficacy, and potentially increased drift. The primary objective of this study was to measure and document the flow and variability of 48 different VeriRate variable-rate aerial nozzles (Spray Target Inc., Rosemount, Minn.) at constant pressures ranging from 207 to 483 kPa (30 to 70 psi). This range was selected because it represents typical spray pressures that an aerial applicator might use. The manufacturer recommended a typical operating pressure range of 207 to 414 kPa (30 to 60 psi) with a maximum operating pressure of 690 kPa (100 psi). A secondary objective of the study was to test for differences in flow rate between nozzles based on starting at 483 kPa and reducing pressure as opposed to starting at a lower pressure and increasing test pressure, based on conversations with the manufacturer.

MATERIALS AND METHODS

Forty-eight new VeriRate nozzles were randomly assigned a unique identification number and flow tested according to ASAE EP367.2 standard testing protocol (*ASABE Standards*, 2008). Each of the nozzles had been used for less than 10 h and was cleaned in an ultrasonic cleaner (Bransonic 5510R-MT, Branson Ultrasonics, Danbury, Conn.) for 1 h prior to testing to ensure optimal performance of the nozzles. Initially, the nozzles were mounted one at a time at the seventh outboard nozzle position on a full-sized standard slip-stream aerial boom with 3.18 mm (0.125 in.) nozzle ports (fig. 2). The plumbing to the nozzle and check valve remained the same for each of the nozzles tested. A calibrated (±1.0 psi), glycerin-filled pressure gauge (CountyLine 2-1/2 in. Liquid-Filled Pressure Gauge; 100 psi, Tractor Supply Co., Brentwood, Tenn.) was mounted at the first nozzle position to monitor boom pressure while the pressure was set each time with a 5.1 cm (2.0 in.) ball valve (Model 8201-DN50, Hammond Valve, New Berlin, Wis.). Before testing, the far outboard nozzle was briefly opened to purge air from the boom. A custom spray tank and pump system were used to provide pressurized water to the boom (fig. 3). The pump system consisted of a 246 L (65 gal) water tank and a 9 hp gas engine driven centrifugal pump (HYPRO Model 1550, Pentair, Ltd., New Brighton, Minn.) which could provide flowrates up to 568 L min^{-1} (150 GPM) and pressures up to 965 kPa (140 psi).

The aerial variable-rate nozzles were tested one at a time in assigned numerical order. The first nozzle was tested at 207 kPa (30 psi), then 276 kPa (40 psi), 345 kPa (50 psi), 414 kPa (60 psi), and 483 kPa (70 psi) with three replicates at each pressure. The flowrates were calculated by

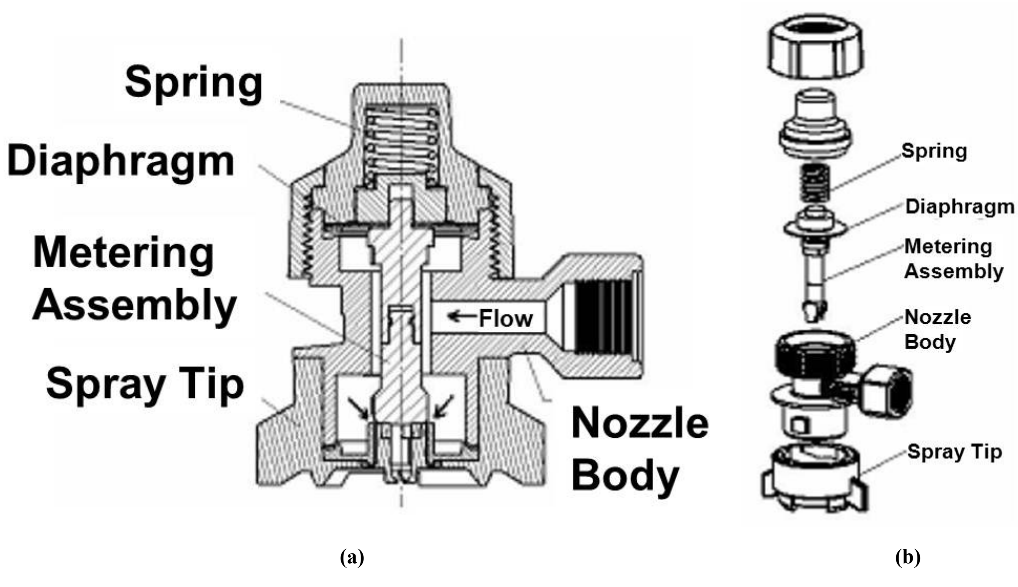

Figure 1. Cross-section (a) and component views (b) of the VeriRate nozzle showing nozzle design and assembly.

Figure 2. VeriRate nozzles being flow tested on a standard slipstream aerial boom.

discharging the spray into a digital sprayer calibration unit (SpotOn Sprayer Calibrator, Model SC-4, Innoquest, Inc., Woodstock, Ill.) with an accuracy of ±4% in accordance with ASAE EP367.2 Guide for Preparing Field Sprayer Calibration Procedures (*ASABE Standards*, 2008). Spray pressure was first applied to the nozzle with the valve open to achieve steady-state conditions prior to flow testing. Once steady-state conditions were achieved, the sprayer calibration unit was inserted into the spray stream to collect spray discharge. The calibration unit had an electrode at the bottom of the unit and one closer to the top. The unit determined the time from when the collected spray volume first contacted the lower electrode to when it contacted the upper electrode. Knowing the volume between the electrodes, the unit calculated the flowrate by dividing this volume by the elapsed time. The flowrates were averaged over the collection period of time, which varied according to flowrate, given the constant volume of spray collected with the calibration unit. At higher pressures, turbulence from the spray into the sprayer calibrator seemed to prematurely activate the electrode used to terminate the measurement. To minimize this turbulence, a 30.5 cm (12 in.) length of 5.1 cm (2 in.) flexible PVC tubing was used to direct the spray from the nozzle to the calibrator. After the flowrates for three replicates were recorded, the flow to the nozzle was cut off by a petcock valve at the nozzle, the nozzle was removed, and the next nozzle was installed at the same position. The petcock valve was then re-opened allowing water to flow through. During this time, the pressure to the new nozzle was adjusted appropriately. Since changing boom pressure with the large manual ball valve was time consuming and relatively difficult to accurately set, the next nozzle was first tested at the existing 483 kPa (70 psi), then 414 kPa (60 psi), etc. This protocol was chosen because it reduced nozzle changes and was similar to what would be required of the nozzles in practice.

Statistical Analysis

Analysis of variance was conducted using the PROC TTEST procedure in SAS (SAS Institute, 2001). The Folded F method (SAS Institute, 2001) was used to determine equality of variances. When t-values were significant at the 5% level, means were separated using the Satterthwaite method (SAS Institute, 2001) for datasets of unequal variance. The coefficient of variation (CV) is widely used to describe data variability. It was calculated by dividing the standard deviation by the mean and was computed using the composite flowrate data for all of the nozzles at a given pressure.

Results and Discussion

Flowrate results from the entire set of 48 nozzles are shown in table 1. Analysis of these data showed that the VeriRate nozzle is capable of achieving a 7X rate change with changes in pressure between 207 and 483 kPa (30 and 70 psi). However, excessive variability (CV>25%) was documented in flow between nozzles at pressures of 207 and 276 kPa (30 and 40 psi), which is unacceptable (*ASABE Standards*, 2007). The range of flowrates between nozzles at 207 kPa (30 psi) spanned from 1.44 to 4.05 L min^{-1} (0.38 to 1.07 GPM) (fig. 4). No one nozzle stood out from the rest. As the pressure increased, the variability in flow between nozzles decreased. At the highest pressure (483 kPa, 70 psi), there was still close to 9.58% variability. These results are consistent with previous nozzle flowrate studies conducted by Dilawari et al. (2008) that showed similar flowrate inconsistencies between nozzles for the

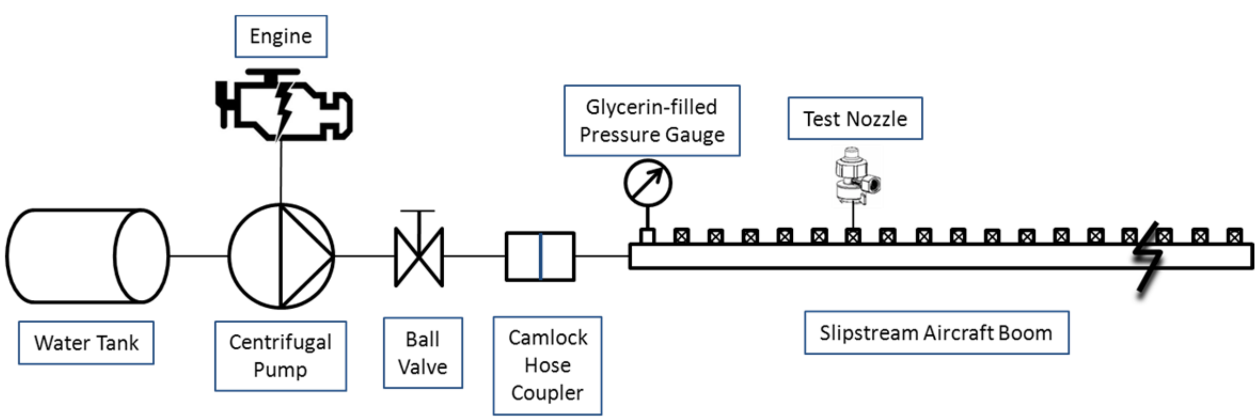

Figure 3. Schematic of spray testing system.

Table 1. Mean flowrates (± SD) of 48 VeriRate nozzles tested at constant pressures from 207 to 483 kPa (30 to 70 psi).[a]

Pressure, kPa (psi)	Mean Flowrate, L min^{-1} (GPM)	CV, %	Range, L min^{-1} (GPM)
207 (30)	2.50 ± 0.64 (0.66 ± 0.17)	25.65	1.44-4.05 (0.38-1.07)
276 (40)	3.66 ± 0.95 (0.97 ± 0.25)	25.91	1.89-5.75 (0.50-1.52)
345 (50)	5.13 ± 1.03 (1.36 ± 0.27)	20.09	3.18-7.15 (0.84-1.89)
414 (60)	6.72 ± 0.77 (1.78 ± 0.20)	11.42	5.11-8.63 (1.35-2.28)
483 (70)	8.20 ± 0.79 (2.1657 ± 0.2074)	9.58	7.08-10.45 (1.87-2.76)

[a] Range indicates the lowest measured rate at a given pressure to the highest measured rate at that pressure for the entire set of nozzles.

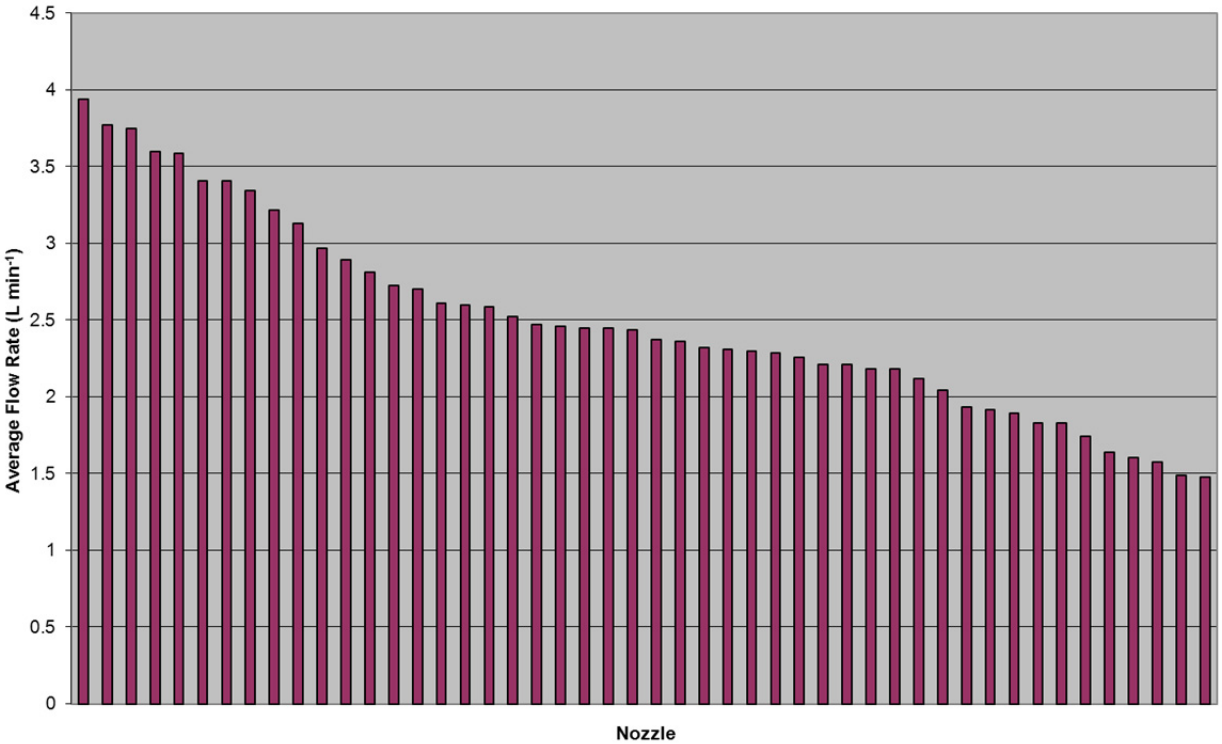

Figure 4. Average flowrates of 48 different VeriRate nozzles tested at 207 kPa (30 psi). The nozzles were sorted by flowrate and plotted in order of descending flowrate to show range of values.

VariTarget nozzle, a variable-rate nozzle for ground applications introduced earlier by the same manufacturer (Bui, 2005). Additional flowrate and droplet spectrum testing of the VariTarget nozzle was conducted by Daggupati (2007).

Subsequent discussions with the manufacturer revealed that the nozzle works best when the pressure is initially spiked, so as to unseat the diaphragm on the metering assembly from the nozzle body. Taking this into account, the dataset was subdivided between nozzles which were initially tested at low pressure, followed by a gradual increase in pressure (T1, n=24), and those which were initially tested at high pressure, followed by a gradual decrease in pressure (T2, n=24). The results from this follow-up analysis are presented in table 2.

Striking differences were revealed in both mean flowrate and flow variability when the two data sets were analyzed independently. Again, the only difference procedurally between the two data sets was that for T1, the pressure was set at 207 kPa (30 psi), flowrate was measured at the nozzle, and then the pressure was increased to 276 kPa (40 psi). This procedure was repeated until the nozzle was tested at 483 kPa (70 psi). The other set of nozzles was first tested at 483 kPa (70 psi), then 414 kPa (60 psi), on down to 207 kPa (30 psi) (T2). Overall, starting at 483 kPa (70 psi) and then reducing pressure gradually (T2), resulted in higher flowrates from the set of nozzles and less variability between nozzles. A hysteresis effect also was

Table 2. Mean flowrates (± SD) of 48 VeriRate nozzles tested at constant pressures from 207-483 kPa (30 - 70 psi).

	T1		T2	
Pressure, kPa (psi)	Mean Flowrate[a], L min^{-1} (GPM)	CV, %	Mean Flowrate[a], L min^{-1} (GPM)	CV, %
207 (30)	2.35 ± 0.72 a (0.62 ± 0.19)	31.03	2.65 ± 0.49 b (0.70 ± 0.13)	18.79
276 (40)	3.26 ± 1.17 a (0.86 ± 0.31)	35.70	4.05 ± 0.95 b (1.07 ± 0.25)	8.91
345 (50)	4.62 ± 1.17 a (1.22 ± 0.31)	25.40	5.64 ± 0.49 b (1.49 ± 0.13)	8.39
414 (60)	6.47 ± 0.91 a (1.71 ± 0.24)	14.32	7.00 ± 0.42 b (1.85 ± 0.11)	6.17
483 (70)	8.10 ± 0.76 a (2.14 ± 0.20)	9.32	8.29 ± 0.79 a (2.19 ± 0.21)	9.69

[a] Flowrates at a given pressure that share a common letter are not statistically different from one another according to the Satterthwaite t-test (α = 0.05).

observed when transitioning from T1 to T2. The flowrates always remained higher at comparable pressure settings when first "spiked" with 483 kPa (70 psi) of pressure. Overall flowrate changes of 3.4X (2.35 to 8.10 L min^{-1}) for T1 and 3.1X (2.65 to 8.29 L min^{-1}) for T2 were documented from the tests. Both of these flowrate changes are better than a 2X change for conventional fixed-orifice hydraulic nozzles but shy of the 5X change typically desired for variable-rate aerial application.

At the various pressure settings, there were differences in the mean flowrate and flow variability (as quantified by coefficient of variation) between VeriRate nozzles tested under the two regimes. It can be seen that the flowrate at 207 kPa (30 psi) for T1 was much lower than T2 (t=-3.03; *df*=125.79; P=0.0030). The flow variability, however, was much higher for T1 than T2 (CV=31.03% vs. 18.79%). Although the flow variability for T2 was lower than T1 at 207 kPa (30 psi), both were unacceptable because they exceeded the 10% standard (ASABE Standards, 2007). The flow variability of T1 at 276 kPa (40 psi) was 4 times greater than that of T2. Differences still existed in flowrate and flow variability between T1 and T2 (t=-5.61; *df*=84.64; P<0.0001) at this pressure, but the flow variability for T2 fell within acceptable levels (CV=8.91%). At 345 kPa (50 psi), the flowrate of T1 was still lower than T2 (t=-6.95; *df*=93.64; P<0.0001), but the flow variability had decreased to 25.40%, or three times that of T2. At 414 kPa (60 psi), there still were differences in flowrate between treatments (t=-4.48; *df*=100.58; P<0.0001), but the flow variability for T1 continued to decrease (CV=14.32%) and declined to only twice that of T2. At 483 kPa (70 psi), all differences between treatments disappeared and flow variability between nozzles was acceptable for both treatments.

The mechanics of the VeriRate nozzle, due to its unique design, give insight and understanding to the observed results. When pressure is applied to the nozzle, a metering assembly pushes back against a spring, enlarging a flexible metering orifice, thus providing flow through the nozzle. When pressure is first applied, the metering assembly is more resistant to movement, but increasing pressure can overcome this initial resistance. Based on the results of this study, at least 483 kPa (70 psi) of pressure must first be applied to the nozzle to adequately move the metering assembly. When lower initial pressures are applied to the nozzles, the flow variability between nozzles exceeds acceptable standards. Automatic flow controllers will increase the pressure to the spray system until the average target application rate is achieved, so overall application rate is not an issue. The primary potential issue is poor pattern uniformity from nozzles producing different flowrates. With 25 to 35% flow variation among the nozzles, some areas of the field may receive the proper rate, some may receive less than the needed amount, and other areas may receive more chemical than is needed. With ground application equipment, this would definitely be the case. However, with aerial applications, mixing of the spray from turbulence, prop wash and other factors may offset some between-nozzle flowrate variability. At stake is efficacy, or the ability of a spray application to protect against crop pests or enhance crop productivity. If it were possible to spike the pressure on the spray system prior to a spray run and avoid spraying system pressures below 276 kPa (40 psi), the flow variability problems would be resolved. To the author's knowledge, no such spray system currently exists. Additionally, some aerial applicators may find this type of variable-rate nozzle to be advantageous for routine spray jobs where the same product is needed on two different fields at different rates. Instead of the applicator having to return to base to change nozzle settings for a different rate, the applicator would merely have to adjust boom pressure in-flight to achieve the new rate. However, based on the performance of the VeriRate nozzles in this study, the applicator would have to manually spike the pressure immediately prior to each pass, and then adjust the pressure to achieve the desired rate. This would not be practical.

CONCLUSIONS

The VeriRate retrofit variable-rate aerial nozzle fills a void in the aerial application industry. Flowrates and flow variability from a set of 48 VeriRate nozzles were measured and documented. This study has shown that a 3.4X flowrate change can be achieved by changing pressure alone between 207 and 483 kPa (30 and 70 psi). Currently, no other conventional hydraulic nozzle can produce this magnitude of rate change under normal system operating pressures. However, flow variability between nozzles exceeded industry standards when pressures remained below 483 kPa (70 psi). In order to achieve acceptable flow variability between nozzles, the VeriRate nozzles had to first be "spiked" with at least 483 kPa (70 psi) of pressure before adjusting to the desired pressure and operated at or above 276 kPa (40 psi). Future work needs to document flowrate performance for a recently released, modified design of the nozzles.

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