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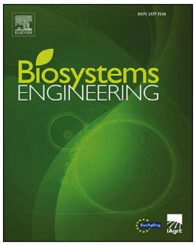

Research Paper

Droplet size and nozzle tip pressure from a pulse-width modulation sprayer

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Pulse-width modulation (PWM) sprayers can improve application accuracy through flow control, turn compensation, and high-resolution overlap control by pulsing an electronically-actuated solenoid valve which controls the relative proportion of time each solenoid valve is open (duty cycle). The objective of this experiment was to identify the droplet size distribution and nozzle tip pressure when influenced by PWM duty cycle, nozzle technology, and gauge pressure to provide PWM guidelines. The experiment was conducted in a low-speed wind tunnel at the Pesticide Application Technology Laboratory using a SharpShooter® PWM system. In general, for non-venturi nozzles, as duty cycle decreased, droplet size slightly increased between 40 and 100% duty cycles. Conversely, venturi nozzles did not always follow this trend. The lowest duty cycle evaluated (20%) negatively impacted droplet size and caused inconsistencies for all nozzle by pressure combinations. The addition of a solenoid valve lowered nozzle tip pressure while gauge pressure remained constant indicating a restriction is present within the solenoid valve. Greater orifice sizes increased the pressure loss observed. Duty cycle minimally impacted nozzle tip pressure trends which were similar to the electrical square wave PWM signals. However, venturi nozzles deviated from this trend, specifically twin-fan, single pre-orifice venturi nozzles. In conclusion, venturi nozzles are not recommended for PWM systems as they may lead to inconsistent applications, specifically in regards to droplet size generation and nozzle tip pressures. Spray pressures of 276 kPa or greater and PWM duty cycles of 40% or greater are recommended to ensure proper PWM operation.

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Nomenclature

a_0, µm	Y-intercept of polynomial regression
a_n, µm	Constant coefficients of polynomial regression
$D_{v0.1}$, µm	Droplet diameter such that 10% of the spray volume was contained in droplets < stated diameter
$D_{v0.5}$, µm	Droplet diameter such that 50% of the spray volume was contained in droplets < stated diameter
$D_{v0.9}$, µm	Droplet diameter such that 90% of the spray volume was contained in droplets < stated diameter
driftable fines, %	Spray volume with droplets ≤150 µm
duty cycle, %	Relative proportion of time solenoid valve is open
x,%	Duty cycle
AMS	Ammonium sulphate
ANOVA	Analysis of variance
LSD	Least significant difference
PWM	Pulse-width modulation
r^2	Coefficient of determination

1. Introduction

Pesticide input costs have increased in the United States by US $5.35 billion over the past decade with weed management comprising the largest portion of these applications as greater than 92% by area of corn (maize) (*Zea mays L.*), soybean [*Glycine max (L.) Merr*], and cotton (*Gossypium hirsutum L.*) areas were treated for weeds in 2015 (USDA-NASS, 2015). The complexity of pesticide applications (Ebert, Taylor, Downer, & Hall, 1999) has led to reports of inaccurate and inefficient sprayer performance (Bish & Bradley, 2017; Grisso, Dickey, & Schulze, 1989; Ozkan, 1987). In current production agricultural systems, this is unacceptable. More precise and efficacious pesticide applications are necessary to meet regulatory demands, increase crop yield potential, and reduce the selection pressure for the evolution of herbicide resistance.

Agricultural pesticides are typically applied in a spray solution atomized by hydraulic nozzles creating a heterogeneous mixture of droplet sizes within the spray pattern (Matthews, Bateman, & Miller, 2014). The resulting spray droplet sizes are determined by numerous factors and the complex interactions between them such as spray solution chemistry (Bouse, Kirk, & Bode, 1990; Butler Ellis, Tuck, & Miller, 1997; Chapple, Downer, & Hall, 1993), nozzle orifice size (Barnett & Matthews, 1992; Nuyttens, Baetens, De Schampheleire, & Sonck, 2007; Nuyttens, De Schampheleire, Verboven, Brusselman, & Dekeyser, 2009), nozzle design technology (Bouse, 1994; Butler Ellis et al., 2002; Nuyttens et al., 2007, 2009), and application pressure (Barnett & Matthews, 1992; Bouse, 1994; Nuyttens et al., 2007; Young, 1990). Creech, Henry, Fritz, and Kruger (2015) determined nozzle design and application pressure caused the greatest changes in spray droplet size. Previous research highlighted the importance of droplet size on drift mitigation (Bueno, da Cunha, & de Santana, 2017; Hewitt, 1997; Johnson, Roeth, Martin, & Klein, 2006) and herbicide efficacy (Etheridge, Womac, & Mueller, 1999; Knoche, 1994; Meyer, Norsworthy, Kruger, & Barber, 2016). Furthermore, homogenisation of the droplet sizes represented within a spray pattern coupled with reduced droplet velocities could result in greater droplet adhesion to leaf surfaces and increase biological efficacy, while limiting drift potential (De Cock, Massinon, Salah, & Lebeau, 2017).

Pulse-width modulation (PWM) sprayers allow for several factors, including application pressure and spray droplet size, to be standardized across a range of sprayer speeds while variably controlling flow to increase application precision. Flow is controlled by pulsing an electronically-actuated solenoid valve placed directly upstream of the nozzle (Giles & Comino, 1989). The flow is changed by controlling the relative proportion of time each solenoid valve is open (duty cycle). This system allows real-time flow rate changes to be made without manipulating application pressure as in other variable rate spray application systems (Anglund & Ayers, 2003). Additionally, PWM solenoid valves buffer some negative impacts, such as spray boom velocity variation during turning movements and flow on/off latency of automatic boom shutoffs, observed with other rate controller systems (Luck, Sharda, Pitla, Fulton, & Shearer, 2011; Sharda, Fulton, McDonald, & Brodbeck, 2011; Sharda, Luck, Fulton, McDonald, & Shearer, 2013). Application pressure based variable rate flow control devices have been shown to have slow response time and affect nozzle performance, specifically droplet size (Giles & Comino, 1989). Previous PWM research illustrated little to no effect from duty cycle on spray droplet size (Giles & Comino, 1990; Giles, Henderson, & Funk, 1996); however, only non-venturi nozzles and nozzles lacking a pre-orifice were evaluated.

PWM sprayers provide the possibility for more precise applications through automatic boom and individual nozzle shut off controls (Luck, Pitla, et al., 2010; Luck, Zandonadi, Luck, & Shearer, 2010) and minimizing changes in droplet trajectory and velocity (Butts, Hoffmann, Luck, & Kruger, 2017; Giles, 2001; Giles & Ben-Salem, 1992). Furthermore, pulsing dual nozzle configurations increased coverage of Palmer amaranth (*Amaranthus palmeri* S. Wats.) while simultaneously minimizing the drift potential of small droplets (Womac et al., 2017; Womac, Melnichenko, Steckel, Montgomery, & Hayes, 2016). One drawback to PWM application systems has been the inability to create wide ranges of droplet distributions because venturi nozzles are not recommended (Capstan Ag Systems Inc., 2013). However, previous research demonstrated there are commercially available, non-venturi nozzles that can produce the range of droplet size distributions needed to reduce drift potential (Butts, Geyer, & Kruger, 2015).

Current nozzle technologies and application parameters must be evaluated on PWM sprayers to determine best use practices for the equipment. The objective of this experiment was to identify the droplet size distribution and pressure at the nozzle tip as influenced by PWM duty cycle, current nozzle technology (venturi versus non-venturi), and gauge application pressure, and provide guidelines for optimal PWM use.

2. Materials and methods

2.1. Experimental design

Research was conducted in the spring and summer of 2016 to evaluate the effect of nozzle type, PWM duty cycle, and gauge application pressure on droplet size distribution and nozzle tip pressure. The experiment was conducted using the low-speed wind tunnel at the Pesticide Application Technology Laboratory located at the West Central Research and Extension Center in North Platte, NE. Creech et al. (2015) and Henry, Kruger, Fritz, Hoffmann, and Bagley (2014) provide further details regarding the low-speed wind tunnel framework and operation. The wind tunnel was equipped with a SharpShooter® PWM system (Capstan Ag Systems, Inc., Topeka, KS) to select the specific duty cycle for each treatment.

The experiment was a 12 × 6 × 3 × 2 factorial cumulating in a total of 432 treatments, and each treatment was replicated three times (three separate nozzle traverses across the laser). The treatments consisted of 12 nozzle types, 6 PWM duty cycles, 3 gauge application pressures (pressure before the solenoid valve), and 2 spray solutions (Table 1). Droplet size and nozzle tip pressure of water were also measured for the 12 nozzle types at the 3 gauge application pressures in a standard nozzle body configuration (no solenoid valve). Glyphosate (Roundup PowerMAX®, Monsanto Co., St. Louis, MO 63167) plus ammonium sulphate (AMS) solution was applied at 0.87 kg ae ha^{-1} and 1.91 kg ha^{-1}, respectively, in a carrier volume of 94 L ha^{-1} to assess whether an active ingredient within the spray solution would affect droplet size and nozzle tip pressure trends when pulsed compared to water alone. Reference nozzles were used to determine spray classifications (ASABE, 2009) and allow for comparisons between testing laboratories (Fritz et al., 2014). Air temperature, solution temperature, and relative humidity were also recorded during the time periods the experiment was conducted.

2.2. Droplet size distribution collection

The droplet size distribution for each treatment was measured using a Sympatec HELOS-VARIO/KR laser diffraction system with the R7 lens (Sympatec Inc., Clausthal, Germany). The laser was linked with WINDOX 5.7.0.0 software (Sympatec Inc.) operated on a computer adjacent to the laser. The R7 lens measures droplets in a dynamic size range from 18 to 3500 μm. The laser consists of two main components, an emitter housing containing the optical box and the source of the laser, and a receiver housing containing the lens and detector element (Fig. 1). The two laser housings are separated (1.2 m) on each side of the wind tunnel and mounted on an aluminum optical bench rail that was connected underneath the wind tunnel to maintain proper laser alignment. The laser was beamed through two 10-cm holes bored into the Plexiglass wind tunnel side wall. The spray plume was oriented perpendicular to the laser and traversed at 0.2 m s^{-1} using a mechanical linear actuator. The distance from the nozzle tip to the laser was 30 cm. The wind tunnel generated a 24 km h^{-1} airspeed in which measurements were recorded (Fritz, Hoffmann, Bagley, et al., 2014). The laser diffraction system provided multiple categories to compare the spray droplet distributions of each treatment. The treatments in this study were compared using the $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ parameters which represent the droplet diameters such that 10, 50, and 90% of the spray volume was contained in droplets of smaller diameter, respectively. Furthermore, the percent of spray volume with droplets ≤150 μm [referred to as driftable fines throughout (Hewitt, 1997)] were recorded for each treatment.

Table 1 – Nozzles (12), pulse-width modulation duty cycles (7), gauge application pressures (3), and spray solutions (2) evaluated in a factorial arrangement of treatments in this research.

Broadcast nozzles					
Abbreviation	Name	Design	Duty cycle %	Gauge pressure kPa	Spray solution
AITTJ-6011004[a]	Air Induction Turbo TwinJet	Venturi	Standard[e]	207	Water alone
AM11002[b]	Airmix	Venturi	100	276	Glyphosate plus ammonium sulphate (AMS)[f]
AM11004[b]	Airmix	Venturi	80	414	
AMDF11004[b]	Airmix DualFan	Venturi	60		
AMDF11008[b]	Airmix DualFan	Venturi	50		
GAT11004[c]	GuardianAIR Twin	Venturi	40		
TTI11004[a]	Turbo TeeJet Induction	Venturi	20		
DR11004[d]	Combo-Jet Drift Control	Non-Venturi			
ER11004[d]	Combo-Jet Extended Range	Non-Venturi			
MR11004[d]	Combo-Jet Mid Range	Non-Venturi			
SR11004[d]	Combo-Jet Small Reduction	Non-Venturi			
UR11004[d]	Combo-Jet Ultra Drift Control	Non-Venturi			

[a] TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL, USA.
[b] Greenleaf Technologies, Covington, LA, USA.
[c] Pentair Hypro SHURflo plc., Minneapolis, MN, USA.
[d] Wilger Industries Ltd., Lexington, TN, USA.
[e] Standard duty cycle indicates no solenoid valve is equipped.
[f] Glyphosate (Roundup PowerMAX®, Monsanto Co., St. Louis, MO, USA) plus ammonium sulphate (AMS) solution was applied at 0.87 kg ae ha^{-1} and 1.91 kg ha^{-1}, respectively, in a carrier volume of 94 l ha^{-1}.

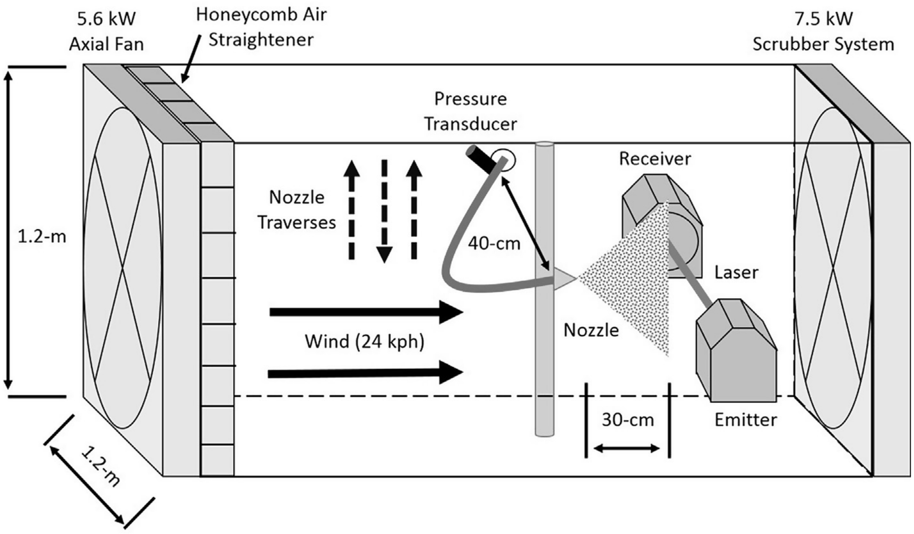

Fig. 1 – Illustration of the low-speed wind tunnel and laser diffraction system used for droplet spectrum analysis at the University of Nebraska–Lincoln Pesticide Application Technology Laboratory located in North Platte, NE.

2.3. *Nozzle tip pressure determination*

The gauge application pressures of 207, 276, and 414 kPa were verified by a PX309, 5 V, 0–689 kPa range pressure transducer (Omega Engineering, Inc., Stamford, CT) located 40 cm upstream from the solenoid valve and connected to a display monitor. The nozzle tip pressure was measured using a similar pressure transducer installed inline between the PWM solenoid valve and nozzle (Fig. 2). The nozzle tip pressure transducer was powered by an 80 W switching mode DC power supply (Extech Instruments, Nashua, NH) which was set to output 10 V. These specific pressure transducers have a silicon sensor protected by a fluid filled stainless steel diaphragm that converts pressure to an analogue electrical signal. The analogue electrical signals were sampled at a 100 Hz rate for 5 s using an Arduino Mega 2560 board (open-source prototyping platform, Arduino.cc). The Arduino board converted the analogue signals to digital and sent them to a serial monitor on a connected computer where the signals were transformed to pressure measurements (kPa).

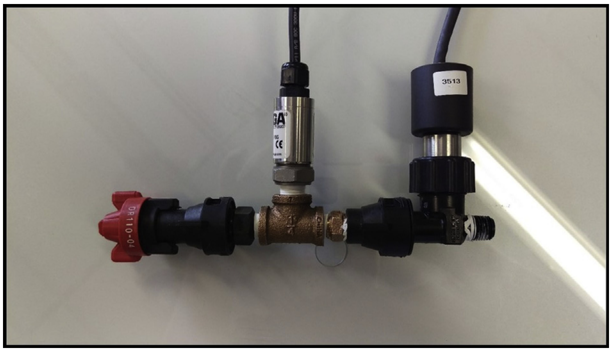

Fig. 2 – Nozzle body and pressure transducer assembly used to measure nozzle tip pressures after the pulse-width modulation solenoid valve. Another pressure transducer was connected inline 40-cm upstream from this assembly to provide gauge application pressure.

2.4. *Statistical analyses*

Regression analysis was conducted on $D_{v0.5}$ values to allow for droplet size predictions as impacted by duty cycle within nozzle type and gauge application pressure and evaluate the variability across nozzle types when pulsed. Seventy different linear, nonlinear, and polynomial models were evaluated to determine best fit using CurveExpert Professional© (v. 2.6.5, Hyams Development). Droplet size parameters, driftable fines, and average nozzle tip pressure data were subjected to analysis of variance (ANOVA) using a mixed effect model in SAS (SAS v9.4, SAS Institute Inc., Cary, NC, USA). Nozzle type, PWM duty cycle, gauge application pressure, and spray solution were treated as fixed effects. Means were separated using Fisher's protected LSD test with the Tukey adjustment to correct for multiplicity. A gamma distribution was used for analysis of droplet size parameters and nozzle tip pressures as data were bound between zero and positive infinity, and a beta distribution was used for analysis of driftable fines as data were bound between zero and one (Stroup, 2013). Back-transformed data are presented for clarity.

3. Results and discussion

The environmental conditions within the Pesticide Application Technology Laboratory were maintained to be relatively constant. The average air temperature and relative humidity throughout the duration of this study was 25 C and 47%, respectively. The average solution temperature across treatments was 21 C. Previous literature suggested less than 5 C difference between air and solution temperatures to minimize variance in droplet size measurements (Hoffmann, Fritz, & Martin, 2011; Miller & Tuck, 2005).

The $D_{v0.5}$ regression over duty cycle analysis revealed that a polynomial regression model (Equation (1)) was among the top fitting models across pressures and nozzles; therefore it was fit to all data. The degree of polynomial (first through

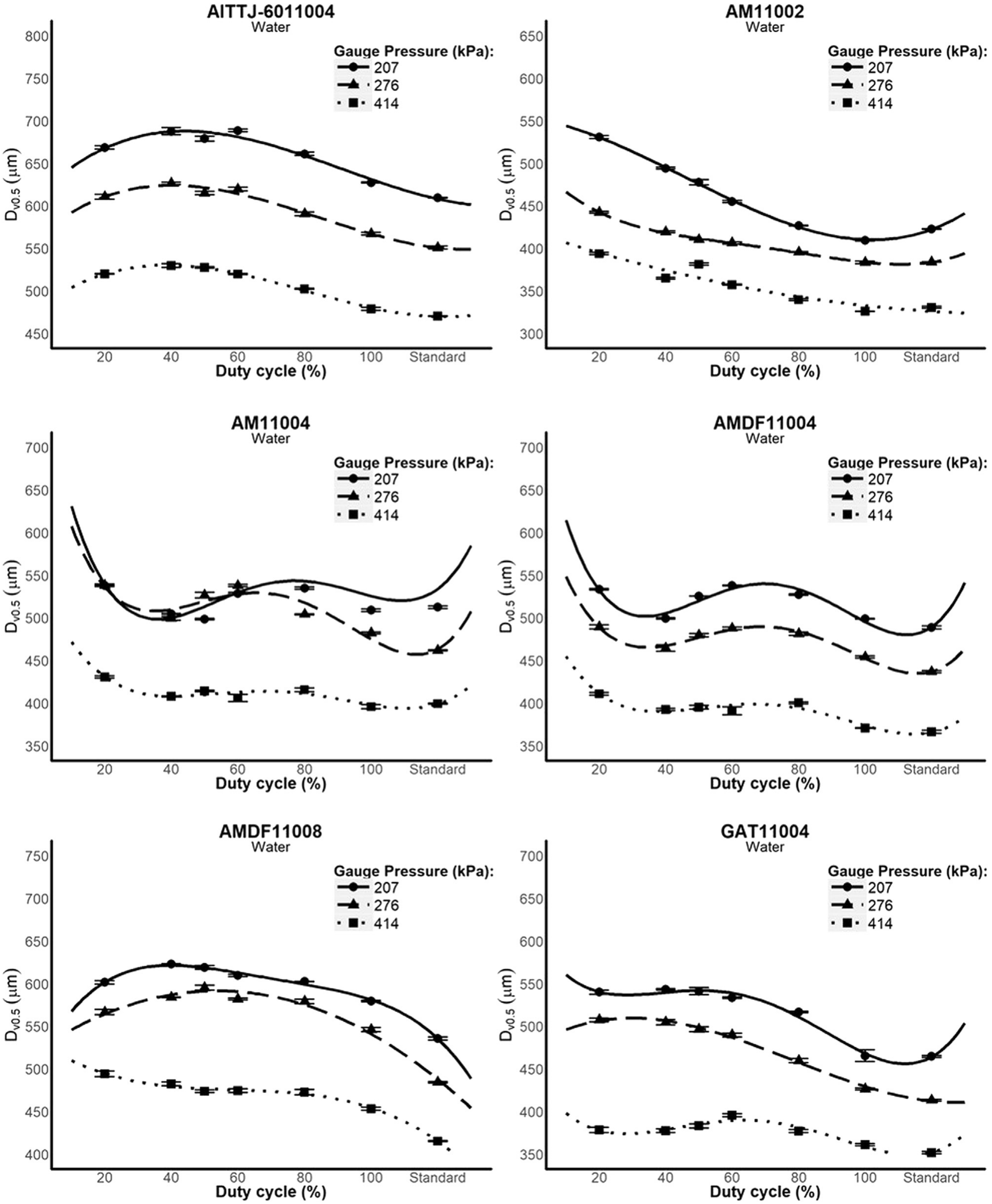

Fig. 3 — Polynomial regressions of droplet size data ($D_{v0.5}$) of water as influenced by duty cycle for the AITTJ-6011004 (top left), AM11002 (top right), AM11004 (middle left), AMDF11004 (middle right), AMDF11008 (bottom left), and GAT11004 (bottom right) nozzles.

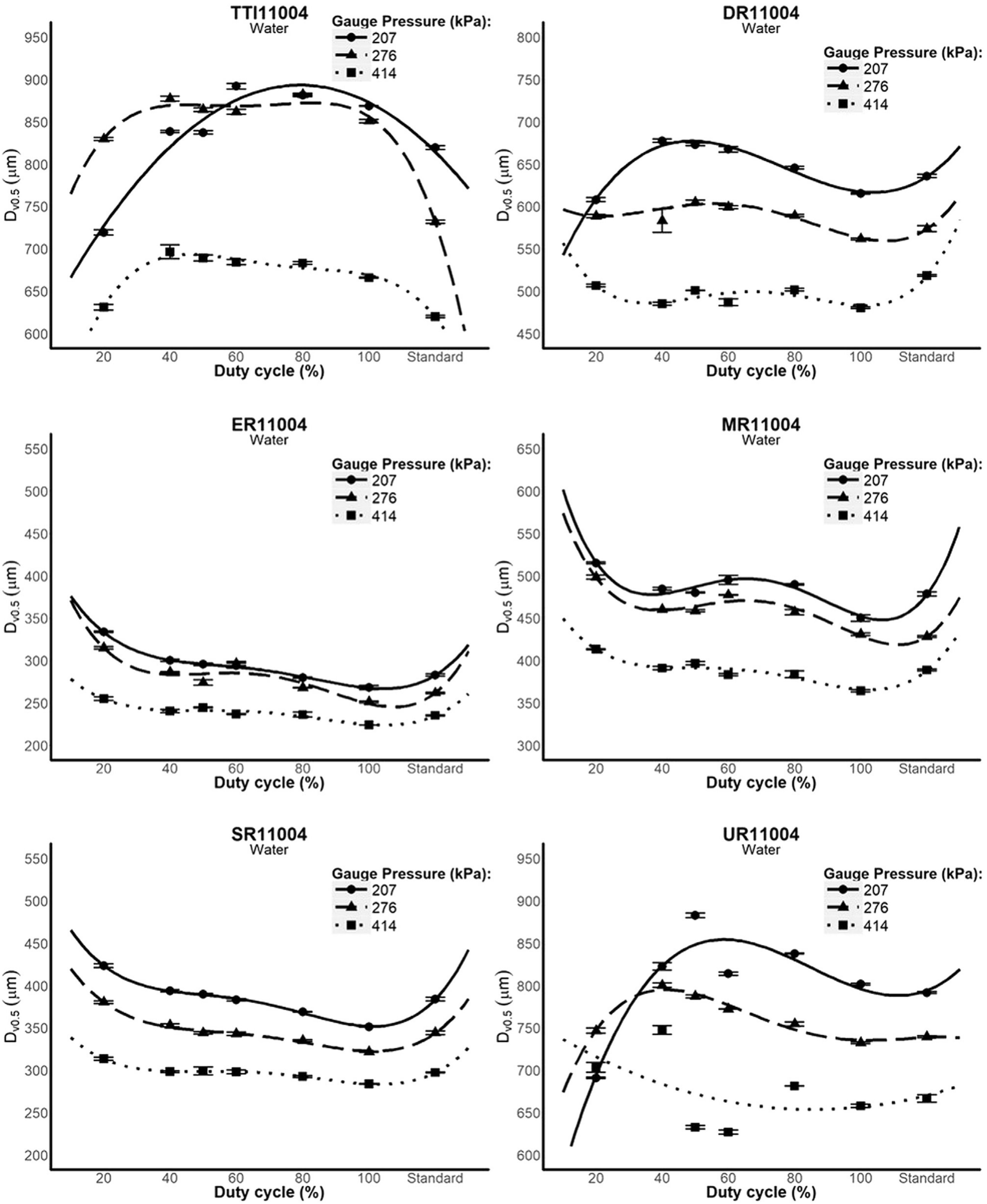

Fig. 4 – Polynomial regressions of droplet size data ($D_{v0.5}$) of water as influenced by duty cycle for the TTI11004 (top left), DR11004 (top right), ER11004 (middle left), MR11004 (middle right), SR11004 (bottom left), and UR11004 (bottom right) nozzles.

fourth degrees) for each treatment was selected based on both the AICC and an *F*-test at $\alpha = 0.01$.

$$D_{v0.5} = a_n x^n + a_{n-1} x^{n-1} + \ldots + a_2 x^2 + a_1 x + a_0 \quad [1]$$

Where $D_{v0.5}$ is droplet diameter such that 50% of the spray volume was contained in droplets of diameter less than the stated diameter, a_0 is y-intercept, a_n is constant coefficients, and x is duty cycle.

Across all response variables, ANOVA resulted in a nozzle*duty cycle*gauge application pressure*solution interaction ($P < 0.0001$). Therefore, comparisons were reduced to strictly observe the effect of PWM duty cycle on droplet size ($D_{v0.1}$, $D_{v0.5}$, $D_{v0.9}$, and driftable fines) within a nozzle, gauge application pressure, and solution. Moreover, for nozzle tip pressure measurements, comparisons were reduced to specifically observe the effect of nozzle type within a solution, gauge application pressure, and PWM duty cycle. Relative trends across analyses were similar for the water and glyphosate plus AMS solutions (data not shown); therefore, the water solution is strictly discussed within this manuscript.

3.1. *Droplet size*

3.1.1. *Venturi nozzles*

Polynomial regressions established for venturi nozzles (AITTJ-6011004, AM11002, AM11004, AMDF11004, AMDF11008,

Table 2 – Polynomial regression parameters (a_0, a_1, a_2, a_3, a_4) and coefficient of determination (r^2) for droplet size ($D_{v0.5}$) regressed over duty cycle of water for each nozzle*pressure combination.

Nozzle	Gauge pressure	a_0	a_1	a_2	a_3	a_4	Coefficient of determination
	kPa	µm					r^2
AITTJ-6011004[a]	207	612.06	3.85	−0.06	2.11 E -04	—	0.96
AM11002[b]	207	552.89	−0.63	−0.03	2.07 E -04	—	0.99
AM11004[b]	207	803.43	−22.31	0.56	−5.47 E -03	1.85 E -05	0.86
AMDF11004[b]	207	777.85	−21.41	0.57	−5.81 E -03	2.02 E -05	0.94
AMDF11008[b]	207	506.68	7.70	−0.18	1.70 E -03	6.06 E -06	0.99
GAT11004[d]	207	608.88	−6.74	0.22	−2.66 E -03	1.05 E -05	0.97
TTI11004[a]	207	595.66	7.51	−0.05	—	—	0.94
DR11004[c]	207	446.70	11.17	−0.17	7.33 E -04	—	0.97
ER11004[c]	207	448.53	−9.13	0.21	−2.11 E -03	7.65 E -06	0.98
MR11004[c]	207	767.14	−21.60	0.56	−5.87 E -03	2.11 E -05	0.91
SR11004[c]	207	540.98	−9.65	0.24	−2.57 E -03	9.84 E -06	0.99
UR11004[c]	207	422.63	17.85	−0.23	9.12 E -04	—	0.86
AITTJ-6011004[a]	276	563.95	3.35	−0.05	2.18 E -04	—	0.97
AM11002[b]	276	503.11	−4.46	0.09	−8.49 E -04	3.00 E -06	0.99
AM11004[b]	276	747.43	−18.38	0.49	−5.06 E -03	1.77 E -05	0.89
AMDF11004[b]	276	665.57	−15.31	0.40	−4.07 E -03	1.39 E -05	0.96
AMDF11008[b]	276	522.78	2.55	−0.02	—	—	0.97
GAT11004[d]	276	476.70	2.41	−0.05	2.13 E -04	—	0.99
TTI11004[a]	276	642.98	15.78	−0.40	4.37 E -03	−1.74 E -05	0.98
DR11004[c]	276	624.47	−4.10	0.15	−1.96 E -03	7.96 E -06	0.94
ER11004[c]	276	475.18	−13.43	0.34	−3.50 E -03	1.26 E -05	0.89
MR11004[c]	276	715.79	−18.31	0.46	−4.65 E -03	1.62 E -05	0.96
SR11004[c]	276	487.27	−8.52	0.20	−2.03 E -03	7.46 E -06	0.97
UR11004[c]	276	550.55	15.30	−0.32	2.60 E -03	−7.28 E -06	0.96
AITTJ-6011004[a]	414	479.36	2.94	−0.05	2.07 E -04	—	0.99
AM11002[b]	414	419.10	−1.30	0.04	—	—	0.89
AM11004[b]	414	546.59	−9.56	0.23	−2.29 E -03	7.86 E -06	0.82
AMDF11004[b]	414	536.24	−10.51	0.26	−2.64 E -03	9.00 E -06	0.89
AMDF11008[b]	414	532.04	−2.62	0.04	−2.36 E -04	—	0.98
GAT11004[d]	414	445.16	−6.41	0.19	−2.16 E -03	7.89 E -06	0.90
TTI11004[a]	414	401.07	18.21	−0.40	3.79 E -03	−1.30 E -05	0.95
DR11004[c]	414	654.99	−12.86	0.34	−3.60 E -03	1.32 E -05	0.74
ER11004[c]	414	321.09	−5.54	0.14	−1.48 E -03	5.45 E -06	0.89
MR11004[c]	414	516.55	−8.66	0.22	−2.36 E -03	8.83 E -06	0.89
SR11004[c]	414	385.76	−6.06	0.15	−1.61 E -03	5.93 E -06	0.88
UR11004[c]	414	759.89	−2.48	0.01	—	—	0.25

[a] TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL, USA.
[b] Greenleaf Technologies, Covington, LA, USA.
[c] Wilger Industries Ltd., Lexington, TN, USA.
[d] Pentair Hypro SHURflo plc., Minneapolis, MN, USA.

GAT11004, and TTI11004) to predict the effect of duty cycle on the $D_{v0.5}$ for each gauge pressure are presented in Figs. 3 and 4. The 20% duty cycle caused severe deviations from observed droplet size trends across other duty cycle treatments (Figs. 3 and 4) resulting in curved tails to the fit models. This duty cycle was determined as the cause of the required polynomial regression as opposed to linear models previously used in PWM droplet size research (Giles & Comino, 1990). It is highly recommended that applicators operate a PWM sprayer at 40% duty cycles or greater. The resulting model parameters and coefficient of determination (r^2) values are presented in Table 2. Generally, as duty cycle decreased, the droplet size increased across venturi nozzles within each gauge pressure. On average, as duty cycle decreased from 100 to 40%, models predicted an increase in droplet size of 0.90, 0.64, and 0.48 μm for every 1% duty cycle decrease for the 207, 276, and 414 kPa gauge pressures, respectively, across venturi nozzles. Although the r^2 values tended to decrease as gauge pressure increased, these results indicate increasing the operating pressure on PWM sprayers can buffer the effect of pulsing on droplet size.

The droplet size distributions and driftable fines of venturi nozzles as affected by pulsing are presented in Table 3 through 6. Across duty cycles, the droplet size distributions from venturi nozzles followed the pattern (from smallest to greatest): AM11002 < GAT11004 < AMDF11004 < AM11004 < AMDF11008 < AITTJ-6011004 < TTI11004 (Tables 3–5).

Table 3 – Droplet size data such that 10% of the spray volume is contained in droplets of lesser diameter ($D_{v0.1}$) for water impacted by duty cycle for nozzle and pressure combinations.

Nozzle	Gauge pressure	$D_{v0.1}$						
		Duty cycle (%)[e]						
		20	40	50	60	80	100	Standard
	kPa	μm						
AITTJ-6011004[a]	207	360 a	359 a	356 a	359 a	340 b	325 c	313 d
AM11002[b]	207	244 a	240 b	234 c	224 d	212 f	203 g	217 e
AM11004[b]	207	261 b	248 e	245 f	258 c	264 a	251 d	263 ab
AMDF11004[b]	207	260 a	248 cd	256 b	259 a	256 b	246 d	249 c
AMDF11008[b]	207	305 b	308 a	306 b	302 c	299 d	289 e	275 f
GAT11004[d]	207	268 a	271 a	270 a	268 a	260 b	234 d	244 c
TTI11004[a]	207	397 e	442 c	439 c	459 a	452 b	449 b	427 d
DR11004[c]	207	309 c	331 a	330 a	329 a	323 b	309 c	330 a
ER11004[c]	207	138 a	128 c	127 c	126 cd	124 d	119 e	132 b
MR11004[c]	207	241 b	230 d	233 cd	236 c	234 c	215 e	247 a
SR11004[c]	207	185 a	174 b	174 b	169 c	166 d	158 e	186 a
UR11004[c]	207	374 f	427 c	446 a	427 c	435 b	419 e	422 d
AITTJ-6011004[a]	276	315 b	318 a	313 b	311 b	297 c	287 d	277 e
AM11002[b]	276	205 a	200 b	197 c	196 d	192 e	187 f	191 e
AM11004[b]	276	255 a	241 d	247 c	250 b	241 d	236 e	230 f
AMDF11004[b]	276	232 a	225 d	226 cd	229 ab	229 bc	218 e	217 e
AMDF11008[b]	276	282 b	280 b	289 a	284 b	280 b	266 c	241 d
GAT11004[d]	276	253 a	253 a	250 b	247 b	233 c	214 d	213 d
TTI11004[a]	276	432 c	443 a	438 b	440 ab	441 ab	429 c	371 d
DR11004[c]	276	297 ab	292 bc	298 a	293 abc	289 c	278 d	293 abc
ER11004[c]	276	129 a	120 b	116 c	128 a	116 c	111 d	120 b
MR11004[c]	276	236 a	220 b	220 b	222 b	215 c	205 e	212 d
SR11004[c]	276	164 a	156 b	152 c	153 c	148 d	143 e	162 a
UR11004[c]	276	397 c	407 a	400 b	392 d	386 e	377 f	387 e
AITTJ-6011004[a]	414	259 a	258 a	258 a	253 b	241 c	231 d	225 e
AM11002[b]	414	168 a	160 c	165 b	160 cd	155 e	150 f	159 d
AM11004[b]	414	194 a	185 cd	184 d	185 cd	188 bc	182 d	191 ab
AMDF11004[b]	414	190 a	183 b	182 bc	180 cd	181 bc	172 e	177 d
AMDF11008[b]	414	231 a	220 b	217 c	216 c	214 c	208 d	198 e
GAT11004[d]	414	178 d	186 b	190 a	193 a	185 b	182 c	174 e
TTI11004[a]	414	310 d	326 a	322 ab	316 cd	319 bc	314 cd	303 e
DR11004[c]	414	243 b	233 d	237 c	234 d	236 c	228 e	259 a
ER11004[c]	414	101 b	97 de	100 bc	98 cd	97 de	96 e	104 a
MR11004[c]	414	188 a	179 b	178 b	176 c	174 c	167 d	189 a
SR11004[c]	414	130 b	127 bc	127 bc	128 bc	125 cd	122 d	137 a
UR11004[c]	414	350 b	361 a	320 f	318 f	335 d	326 e	342 c

[a] TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL, USA.

[b] Greenleaf Technologies, Covington, LA, USA.

[c] Wilger Industries Ltd., Lexington, TN, USA.

[d] Pentair Hypro SHURflo plc., Minneapolis, MN, USA.

[e] Means within a gauge pressure and nozzle with the same letter are not significantly different ($P \leq 0.05$). Standard duty cycle refers to a sprayer configuration with no solenoid valve equipped.

Table 4 – Droplet size data such that 50% of the spray volume is contained in droplets of lesser diameter ($D_{v0.5}$) for water impacted by duty cycle for nozzle and pressure combinations.

Nozzle		$D_{v0.5}$						
		Duty cycle (%)[e]						
	Gauge pressure	20	40	50	60	80	100	Standard
	kPa	μm						
AITTJ-6011004[a]	207	669 c	688 a	679 b	689 a	661 d	627 e	609 f
AM11002[b]	207	531 a	494 b	478 c	455 d	427 e	409 g	423 f
AM11004[b]	207	538 a	505 f	498 g	529 c	535 b	509 e	512 d
AMDF11004[b]	207	533 b	499 d	525 c	538 a	527 c	499 d	489 e
AMDF11008[b]	207	601 d	623 a	619 b	610 c	602 d	579 e	536 f
GAT11004[d]	207	540 ab	543 a	541 ab	534 b	517 c	465 d	465 d
TTI11004[a]	207	719 f	838 d	837 d	892 a	882 b	868 c	819 e
DR11004[c]	207	608 f	677 a	673 a	667 b	646 c	615 e	636 d
ER11004[c]	207	334 a	300 b	296 bc	294 c	280 d	268 e	283 d
MR11004[c]	207	515 a	484 cd	480 d	495 b	490 bc	450 e	478 d
SR11004[c]	207	423 a	394 b	390 c	383 d	369 e	351 f	384 d
UR11004[c]	207	691 g	822 c	883 a	814 d	838 b	801 e	792 f
AITTJ-6011004[a]	276	611 c	626 a	615 bc	620 b	591 d	567 e	551 f
AM11002[b]	276	442 a	419 b	410 c	406 d	396 e	383 f	384 f
AM11004[b]	276	538 a	499 d	526 b	538 a	504 c	482 e	462 f
AMDF11004[b]	276	489 a	464 c	480 b	488 a	481 b	454 d	437 e
AMDF11008[b]	276	567 c	584 b	595 a	582 b	579 b	546 d	484 e
GAT11004[d]	276	507 a	505 a	496 b	490 c	460 d	426 e	413 f
TTI11004[a]	276	829 d	877 a	864 b	862 b	882 a	851 c	732 e
DR11004[c]	276	588 bc	583 cd	605 a	599 ab	589 bc	561 e	574 de
ER11004[c]	276	315 a	286 c	274 d	296 b	268 e	251 g	262 f
MR11004[c]	276	498 a	460 c	458 c	477 b	457 c	431 d	428 d
SR11004[c]	276	380 a	353 b	344 c	343 c	335 d	321 e	344 c
UR11004[c]	276	746 e	800 a	787 b	772 c	755 d	732 g	739 f
AITTJ-6011004[a]	414	520 b	530 a	527 a	520 b	502 c	479 d	470 e
AM11002[b]	414	394 a	365 c	381 b	357 d	340 e	326 g	331 f
AM11004[b]	414	431 a	408 c	414 b	406 c	416 b	396 d	399 d
AMDF11004[b]	414	411 a	393 c	395 bc	391 c	400 b	371 d	366 d
AMDF11008[b]	414	494 a	482 b	474 c	474 c	473 c	453 d	415 e
GAT11004[d]	414	378 bc	377 c	383 b	396 a	377 c	361 d	352 e
TTI11004[a]	414	631 d	696 a	689 ab	684 b	683 b	666 c	620 e
DR11004[c]	414	506 b	485 d	501 c	487 d	501 c	480 e	518 a
ER11004[c]	414	255 a	240 c	244 b	237 d	236 d	224 e	235 d
MR11004[c]	414	413 a	391 c	397 b	383 d	384 d	364 e	389 c
SR11004[c]	414	313 a	298 b	299 b	298 b	292 c	284 d	297 bc
UR11004[c]	414	703 b	747 a	633 e	627 e	681 c	658 d	666 d

[a] TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL, USA.

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[c] Wilger Industries Ltd., Lexington, TN, USA.

[d] Pentair Hypro SHURflo plc., Minneapolis, MN, USA.

[e] Means within a gauge pressure and nozzle with the same letter are not significantly different ($P \leq 0.05$). Standard duty cycle refers to a sprayer configuration with no solenoid valve equipped.

Driftable fines emitted from venturi nozzles were inversely proportional across duty cycles (Table 6). These droplet size patterns were expected according to the nozzle manufacturer's catalogues. For reference, the spray classifications were Coarse, Coarse, Very Coarse, Very Coarse, Very Coarse, Extremely Coarse, and Ultra Coarse for the AM11002, GAT11004, AMDF11004, AM11004, AMDF11008, AITTJ-6011004, and TTI11004 nozzles, respectively, at 276 kPa.

The addition of the solenoid valve to the spray system had variable effects on the droplet size distributions from venturi nozzles. The AITTJ-6011004, AMDF11008, and TTI11004 had greater droplet sizes and reduced or equal driftable fines across gauge pressures when the solenoid valve was operated at a 100% duty cycle compared to the standard configuration (no solenoid valve equipped). This is likely due to an additional restriction or elongated flow path within dual-fan and deflector-type venturi nozzles compared to other nozzles resulting in reduced pressure at the nozzle exit. Previous research corroborates this theory as reductions in droplet velocity from these nozzles were observed when a solenoid valve was equipped and operated at a 100% duty cycle (Butts et al., 2017).

The $D_{v0.1}$, $D_{v0.9}$, and driftable fines from venturi nozzles followed similar trends as model predictions of the $D_{v0.5}$ previously discussed. Typically, as duty cycle decreased, the $D_{v0.1}$ and $D_{v0.9}$ increased, and the driftable fines decreased across venturi nozzles and within gauge pressures. The average increase in $D_{v0.1}$ and $D_{v0.9}$ was 5.6% and 6.7%, respectively,

Table 5 – Droplet size data such that 90% of the spray volume is contained in droplets of lesser diameter ($D_{v0.9}$) for water impacted by duty cycle for nozzle and pressure combinations.

Nozzle		$D_{v0.9}$						
		Duty cycle (%)[e]						
	Gauge pressure	20	40	50	60	80	100	Standard
	kPa	µm						
AITTJ-6011004[a]	207	948 d	997 bc	989 c	1033 a	1003 b	952 d	931 e
AM11002[b]	207	855 a	789 b	734 c	699 d	645 e	600 f	631 e
AM11004[b]	207	808 b	764 d	754 e	832 a	831 a	802 b	788 c
AMDF11004[b]	207	821 d	744 g	841 c	898 a	861 b	796 e	781 f
AMDF11008[b]	207	841 f	983 a	975 b	962 c	949 d	889 e	818 g
GAT11004[d]	207	828 b	852 a	853 a	831 b	829 b	713 c	704 c
TTI11004[a]	207	968 e	1168 d	1164 d	1312 a	1306 a	1287 b	1199 c
DR11004[c]	207	865 e	1043 a	1044 a	1032 a	988 b	945 d	967 c
ER11004[c]	207	631 a	562 b	550 b	536 c	470 d	452 e	466 d
MR11004[c]	207	819 a	746 cd	762 bc	789 ab	790 ab	707 e	726 de
SR11004[c]	207	718 a	665 b	667 b	639 c	588 e	561 f	616 d
UR11004[c]	207	954 g	1172 d	1356 a	1151 e	1254 b	1195 c	1136 f
AITTJ-6011004[a]	276	895 d	937 b	919 c	972 a	933 b	880 e	852 f
AM11002[b]	276	712 a	691 b	672 c	659 d	620 e	590 f	588 f
AM11004[b]	276	857 b	779 d	850 b	931 a	821 c	750 e	713 f
AMDF11004[b]	276	798 c	743 d	788 c	835 a	817 b	747 d	708 e
AMDF11008[b]	276	852 d	954 b	956 b	937 c	978 a	861 d	781 e
GAT11004[d]	276	808 a	823 a	805 a	806 a	737 b	672 c	659 c
TTI11004[a]	276	1233 d	1303 b	1285 c	1276 c	1344 a	1281 c	1099 e
DR11004[c]	276	887 b	887 b	960 a	971 a	943 a	864 b	876 b
ER11004[c]	276	612 a	554 b	503 c	551 b	466 d	423 f	438 e
MR11004[c]	276	810 a	724 c	737 bc	793 a	755 b	689 d	670 e
SR11004[c]	276	667 a	595 b	580 c	573 d	557 f	531 g	563 e
UR11004[c]	276	1084 e	1203 a	1176 b	1149 c	1112 d	1082 e	1084 e
AITTJ-6011004[a]	414	790 d	842 a	838 ab	832 bc	823 c	775 e	778 e
AM11002[b]	414	688 b	645 c	715 a	605 d	559 e	527 f	525 f
AM11004[b]	414	718 a	682 bc	695 b	671 c	712 a	653 d	646 d
AMDF11004[b]	414	685 a	649 bc	658 b	638 c	698 a	585 e	605 d
AMDF11008[b]	414	803 b	821 a	800 b	801 b	795 b	760 c	683 d
GAT11004[d]	414	614 b	597 c	598 c	668 a	618 b	578 d	571 d
TTI11004[a]	414	939 c	1089 a	1066 a	1063 a	1067 a	1018 b	997 b
DR11004[c]	414	801 b	752 d	803 b	773 c	829 a	775 c	816 ab
ER11004[c]	414	505 a	457 b	502 a	445 c	421 d	398 e	407 e
MR11004[c]	414	689 a	655 bc	666 b	630 d	639 cd	584 e	625 d
SR11004[c]	414	571 a	524 b	538 b	536 b	501 c	475 d	482 d
UR11004[c]	414	992 c	1176 a	924 d	911 d	1046 b	1007 c	1006 c

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[e] Means within a gauge pressure and nozzle with the same letter are not significantly different ($P \leq 0.05$). Standard duty cycle refers to a sprayer configuration with no solenoid valve equipped.

across venturi nozzles and within gauge pressures when duty cycle was decreased from 100 to 40%. The effect of pulsing caused complex fluctuations in the droplet diameters across gauge pressures and venturi nozzles as the $D_{v0.9}$ ranged from a decrease of 10.2% to an increase of 24.0% when duty cycle was reduced from 100 to 40%. The general trend would indicate particle drift potential would decrease slightly from a pulsing PWM sprayer operated with venturi nozzles; however, due to the extreme fluctuations of the droplet size distributions and driftable fines emitted from venturi nozzles across a range of duty cycles and gauge pressures, this conclusion cannot be drawn with any certainty. Greater variability within venturi nozzle droplet size distribution measurements compared to non-venturi nozzles was also noted in previous research (Etheridge et al., 1999; Miller & Butler Ellis, 2000). The variability resulted in negative effects on spray pattern (Ayers, Rogowski, & Kimble, 1990) and decreased weed control (Etheridge, Hart, Hayes, & Mueller, 2001). The unpredictable nature of droplet size distributions when affected by pulsing venturi nozzles is simply unacceptable for the optimization and homogenization of PWM sprays.

3.1.2. *Non-venturi nozzles*

Polynomial regressions established for non-venturi nozzles (DR11004, ER11004, MR11004, SR11004, and UR11004) to predict the effect of duty cycle on the $D_{v0.5}$ for each gauge

Table 6 – Percent of spray volume less than 150 μm (driftable fines) for water as impacted by duty cycle for each nozzle and pressure combination.

Nozzle		Driftable fines						
		Duty cycle (%)[e]						
	Gauge pressure	20	40	50	60	80	100	Standard
	kPa	%						
AITTJ-6011004[a]	207	0.09 c	0.54 b	0.56 b	0.55 b	0.63 b	0.71 ab	0.87 a
AM11002[b]	207	2.90 d	2.62 f	2.78 e	3.33 c	3.97 b	4.46 a	3.23 c
AM11004[b]	207	2.27 b	2.55 a	2.60 a	2.16 c	1.97 d	2.33 b	1.79 e
AMDF11004[b]	207	2.12 b	2.32 ab	2.17 b	2.11 b	2.15 b	2.52 a	2.13 b
AMDF11008[b]	207	1.34 c	1.18 e	1.21 e	1.27 d	1.31 cd	1.43 b	1.48 a
GAT11004[d]	207	1.66 c	1.80 c	1.74 c	1.79 c	1.94 bc	2.91 a	2.16 b
TTI11004[a]	207	0.15 b	0.33 ab	0.34 a	0.23 ab	0.24 ab	0.25 ab	0.27 ab
DR11004[c]	207	1.45 a	1.11 c	1.07 c	1.06 c	1.13 c	1.31 b	0.77 d
ER11004[c]	207	11.78 e	14.03 cd	14.36 c	14.45 bc	15.17 b	16.60 a	13.56 d
MR11004[c]	207	3.16 bc	3.44 b	2.98 c	3.12 bc	3.27 bc	4.11 a	2.24 d
SR11004[c]	207	6.18 e	7.14 d	7.01 d	7.55 c	7.92 b	8.90 a	5.60 f
UR11004[c]	207	0.73 a	0.52 b	0.37 d	0.50 b	0.39 d	0.45 c	0.30 e
AITTJ-6011004[a]	276	0.74 f	0.86 e	0.92 de	0.97 d	1.12 c	1.21 b	1.36 a
AM11002[b]	276	4.49 d	4.51 d	4.72 c	4.77 c	5.03 b	5.52 a	5.08 b
AM11004[b]	276	2.09 e	2.61 d	2.70 cd	2.61 d	2.78 bc	2.88 ab	2.92 a
AMDF11004[b]	276	2.90 e	3.12 d	3.32 bc	3.18 cd	3.20 cd	3.72 a	3.39 b
AMDF11008[b]	276	1.45 d	1.73 c	1.53 d	1.63 c	1.70 c	1.97 b	2.36 a
GAT11004[d]	276	1.94 f	2.08 e	2.15 de	2.21 d	2.60 c	3.79 a	3.49 b
TTI11004[a]	276	0.01 d	0.25 c	0.25 c	0.25 c	0.25 c	0.29 b	0.48 a
DR11004[c]	276	1.32 d	1.51 c	1.52 c	1.61 b	1.65 b	1.81 a	1.28 d
ER11004[c]	276	13.67 d	16.09 c	17.32 b	14.26 d	17.28 b	19.32 a	16.90 bc
MR11004[c]	276	2.90 e	3.49 d	3.47 d	3.78 c	4.14 b	4.65 a	3.90 c
SR11004[c]	276	8.11 e	9.09 d	9.63 c	9.58 c	10.21 b	11.05 a	8.15 e
UR11004[c]	276	0.01 f	0.49 d	0.52 c	0.55 b	0.57 b	0.64 a	0.44 e
AITTJ-6011004[a]	414	1.66 f	1.90 e	1.91 e	2.04 d	2.34 c	2.71 b	3.03 a
AM11002[b]	414	7.62 e	8.48 c	7.89 d	8.52 c	9.14 b	9.93 a	8.50 c
AM11004[b]	414	5.07 c	5.86 ab	6.14 a	5.90 ab	5.72 b	6.18 a	5.22 c
AMDF11004[b]	414	5.35 d	5.89 c	6.10 bc	6.40 b	6.33 bc	7.03 a	6.43 b
AMDF11008[b]	414	3.18 f	3.75 e	3.92 de	3.95 cd	4.13 c	4.38 b	4.75 a
GAT11004[d]	414	6.45 a	5.31 c	4.97 d	4.96 d	5.54 bc	5.78 b	6.55 a
TTI11004[a]	414	0.81 c	0.92 bc	0.95 abc	0.95 abc	0.94 abc	1.04 ab	1.08 a
DR11004[c]	414	2.64 d	2.94 c	3.08 b	2.98 bc	3.09 b	3.41 a	1.95 e
ER11004[c]	414	21.72 d	23.82 b	22.93 c	23.86 b	24.25 b	25.58 a	22.22 d
MR11004[c]	414	5.75 d	6.52 c	6.71 c	6.79 bc	7.02 b	7.76 a	5.34 e
SR11004[c]	414	13.35 bc	14.15 b	14.26 ab	13.93 b	14.58 ab	15.42 a	12.17 c
UR11004[c]	414	1.06 ab	0.86 bc	1.05 ab	1.05 ab	1.04 ab	1.14 a	0.70 c

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[e] Means within a gauge pressure and nozzle with the same letter are not significantly different ($P \leq 0.05$). Standard duty cycle refers to a sprayer configuration with no solenoid valve equipped.

pressure are presented in Fig. 4. The resulting model parameters and r^2 values are presented in Table 2. Similar to venturi nozzles, as duty cycle decreased, droplet size increased across non-venturi nozzles (Fig. 4). The non-venturi nozzles required polynomial regressions, similar to the venturi nozzles, which may be an indication that more complex models are needed to appropriately fit droplet size data as affected by pulsing with current nozzle technologies, such as pre-orifice and venturi type nozzles, in contrast to conclusions from previous research using only non-venturi nozzles with no pre-orifice (Giles & Comino, 1990). On average, non-venturi models predicted an increase in $D_{v0.5}$ as duty cycle decreased from 100 to 40% with estimated increases in $D_{v0.5}$ of 0.68, 0.62, and 0.34 μm for every 1% decrease in duty cycle for 207, 276, and 414 kPa gauge pressures, respectively. These increases in droplet size were smaller than those caused by pulsing venturi nozzles; therefore, non-venturi nozzles stabilized the droplet size distributions more than venturi nozzles across a range of duty cycles and would be the preferred nozzle on PWM sprayers. Similar to venturi nozzles, although r^2 values decreased as gauge pressure increased, the increase in gauge pressure buffered the pulsing effect on droplet size, further

Table 7 – Average nozzle tip pressure over five seconds for water as impacted by nozzle for each gauge pressure and duty cycle combination.

Nozzle		Average nozzle tip pressure						
		Duty cycle (%)[e]						
	Gauge pressure	20	40	50	60	80	100	Standard
	kPa							
AITTJ-6011004[a]	207	36 bc	67 bc	83 bc	95 cd	137 d	194 i	210 b
AM11002[b]	207	58 a	106 a	127 a	148 a	196 a	216 a	213 a
AM11004[b]	207	39 b	78 ab	99 ab	118 abc	172 bc	202 f	204 g
AMDF11004[b]	207	39 b	77 b	95 b	114 bc	152 cd	199 g	207 e
AMDF11008[b]	207	27 c	55 c	70 c	86 d	117 e	164 j	197 i
GAT11004[d]	207	35 bc	70 bc	86 bc	103 bcd	157 bc	196 h	209 c
TTI11004[a]	207	41 ab	81 ab	100 ab	118 abc	160 bc	203 f	208 d
DR11004[c]	207	41 ab	80 ab	98 ab	116 abc	161 bc	205 d	207 e
ER11004[c]	207	41 ab	80 ab	97 ab	122 ab	175 ab	206 c	205 f
MR11004[c]	207	42 ab	81 ab	98 ab	121 ab	166 bc	207 b	208 d
SR11004[c]	207	40 b	77 b	96 b	119 abc	157 bc	204 e	203 h
UR11004[c]	207	40 b	79 ab	98 ab	115 bc	163 b	204 e	208 d
AITTJ-6011004[a]	276	47 bcd	88 bc	107 bcd	138 bcd	197 bc	260 g	279 b
AM11002[b]	276	66 a	121 a	149 a	178 a	235 a	276 a	277 c
AM11004[b]	276	56 abc	103 abc	130 abc	147 abc	202 b	256 i	274 f
AMDF11004[b]	276	65 ab	110 ab	137 ab	164 ab	222 ab	273 b	279 b
AMDF11008[b]	276	39 d	78 c	94 d	111 d	153 d	208 j	268 g
GAT11004[d]	276	46 cd	85 bc	104 cd	122 cd	175 c	258 h	277 c
TTI11004[a]	276	57 abc	108 ab	134 abc	160 ab	220 ab	265 d	276 de
DR11004[c]	276	55 abc	104 abc	128 abc	158 ab	209 ab	266 c	283 a
ER11004[c]	276	55 abc	107 ab	134 abc	162 ab	222 ab	261 f	275 ef
MR11004[c]	276	55 abc	107 ab	133 abc	159 ab	222 ab	266 c	283 a
SR11004[c]	276	51 abcd	104 abc	130 abc	156 ab	206 b	265 d	276 d
UR11004[c]	276	54 abcd	106 ab	129 abc	151 abc	211 ab	264 e	278 b
AITTJ-6011004[a]	414	69 bc	132 b	160 bc	202 bc	293 b	392 i	409 f
AM11002[b]	414	105 a	189 a	231 a	278 a	368 a	427 a	418 b
AM11004[b]	414	81 ab	158 ab	196 ab	235 abc	315 ab	400 f	419 a
AMDF11004[b]	414	81 ab	158 ab	196 ab	236 abc	317 ab	399 g	419 a
AMDF11008[b]	414	55 c	121 b	143 c	184 c	246 c	337 j	409 f
GAT11004[d]	414	63 bc	127 b	160 bc	201 bc	292 b	400 fg	409 f
TTI11004[a]	414	81 ab	160 ab	199 ab	240 abc	319 ab	404 d	418 b
DR11004[c]	414	82 ab	161 ab	199 ab	240 abc	320 ab	405 c	416 c
ER11004[c]	414	80 abc	158 ab	196 ab	234 abc	311 b	402 e	411 e
MR11004[c]	414	84 ab	162 ab	203 ab	242 ab	326 ab	410 b	418 b
SR11004[c]	414	79 abc	156 ab	192 abc	232 abc	309 b	398 h	413 d
UR11004[c]	414	82 ab	161 ab	199 ab	236 abc	323 ab	405 c	416 c

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[d] Pentair Hypro SHURflo plc., Minneapolis, MN, USA.

[e] Means within a gauge pressure and duty cycle with the same letter are not significantly different ($P \leq 0.05$). Standard duty cycle refers to a sprayer configuration with no solenoid valve equipped.

validating PWM sprayers should be operated at greater gauge pressures (≥276 kPa) as much as drift mitigation efforts allow.

The $D_{v0.1}$, $D_{v0.5}$, $D_{0.9}$, and driftable fines emitted from non-venturi nozzles as affected by PWM duty cycle are presented in Table 3 through 6. Across duty cycles, the droplet size distributions from non-venturi nozzles followed the pattern (from smallest to greatest): ER11004 < SR11004 < MR11004 < DR11004 < UR11004 (Tables 3–5). Driftable fines emitted from non-venturi nozzles followed the inverse pattern across duty cycles (Table 6). These trends were expected according to the nozzle manufacturer's catalogue. For reference, the spray classifications were Medium, Medium, Coarse, Extremely Coarse, and Extremely Coarse for the ER11004, SR11004, MR11004, DR11004, and UR11004 nozzles, respectively, at 276 kPa. In previous PWM literature, only non-venturi nozzles with no pre-orifice were evaluated (Giles & Comino, 1990; Giles et al., 1996, pp. 23–26). For the non-venturi nozzles evaluated in this research, four out of five (SR11004, MR11004, DR11004, and UR11004) had pre-orifices, and little to no difference was observed in the droplet size trends when pulsed between the non-venturi nozzles with pre-orifices and the non-venturi nozzle without a pre-orifice (ER11004).

The addition of an inline solenoid valve caused a decrease in droplet size when operated at a 100% duty cycle compared to the standard configuration (no solenoid valve equipped) within gauge pressures and across most non-venturi nozzles. This result was peculiar as the nozzle tip pressure data, discussed in detail later in this manuscript, revealed a decrease in pressure across the solenoid valve. Flow rates of non-venturi nozzles across gauge pressures were measured to determine if flow rates were increasing through a solenoid valve to explain the droplet size decrease (data not shown). The addition of a solenoid valve operated at a 100% duty cycle decreased flow rate by approximately 5% compared to the standard configuration, matching the nozzle tip pressure reductions observed from the addition of a solenoid valve (Table 7). Therefore, this does not explain the decrease in droplet size from non-venturi nozzles

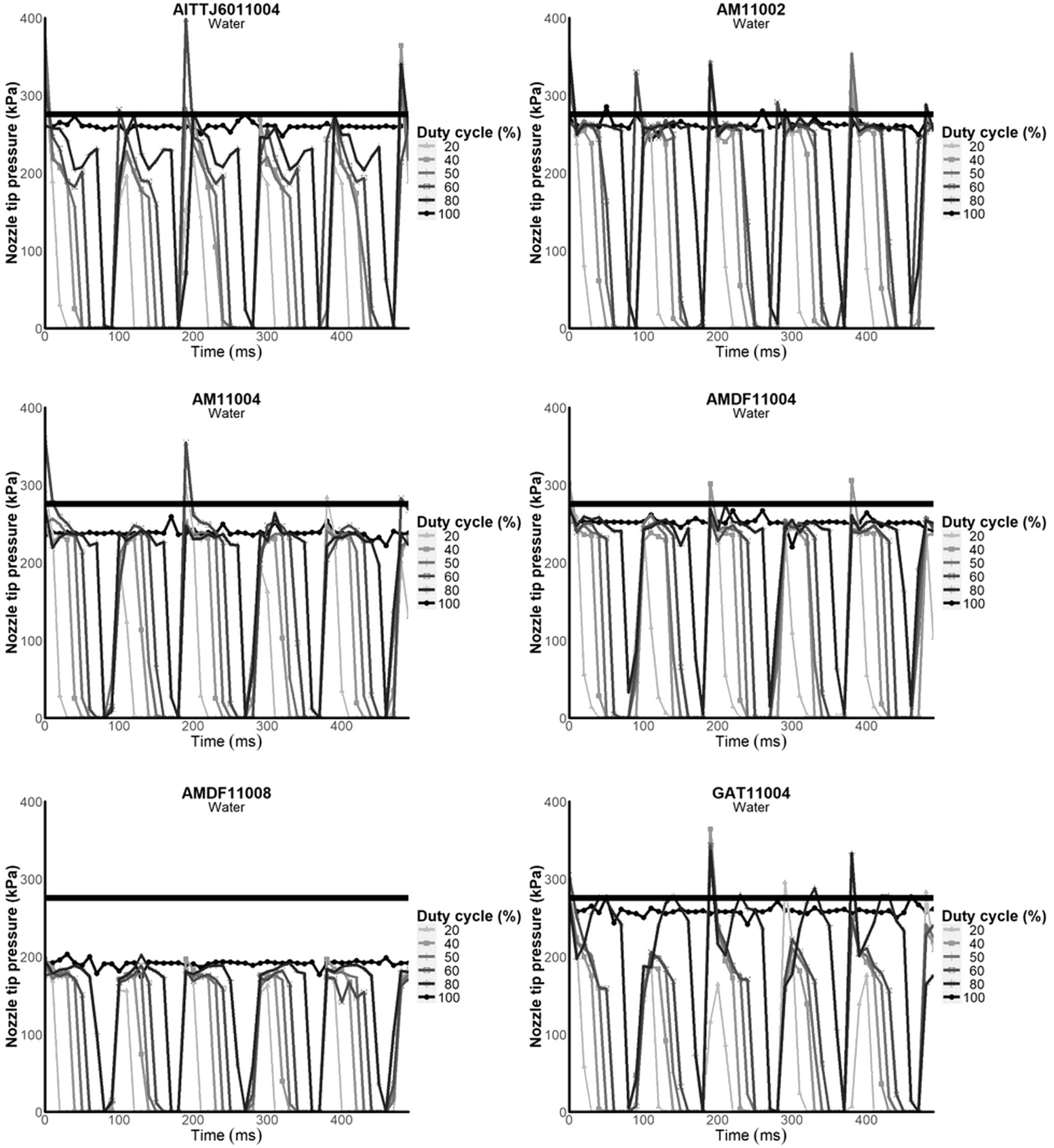

Fig. 5 – Fluctuations in nozzle tip pressure (kPa) over 0.5 s for a gauge pressure of 276 kPa with water spray solution as influenced by duty cycle for the AITTJ-6011004 (top left), AM11002 (top right), AM11004 (middle left), AMDF11004 (middle right), AMDF11008 (bottom left), and GAT11004 (bottom right) nozzles. The solid black bar indicates the 276 kPa gauge pressure.

operated at a 100% duty cycle compared to a standard configuration and further research should be conducted to identify the underlying cause. Overall, the decrease in droplet size indicates PWM sprayers operating with non-venturi nozzles at high duty cycles increase spray drift potential slightly compared to conventional sprayers. However, this increase in spray drift potential is minimal, especially when compared to the drift potential increases observed from conventional sprayers implementing similar flow rate changes (Giles, Downey, Kolb, & Grimm, 2003).

The $D_{v0.1}$ and $D_{0.9}$ generally increased as duty cycle decreased across non-venturi nozzles and gauge pressures similar to the model predictions for the $D_{v0.5}$. The $D_{v0.1}$ and $D_{v0.9}$ increased by an average of 6.0 and 9.6%, respectively, within gauge pressures and across non-venturi nozzles when the duty cycle was reduced from 100 to 40%. The non-venturi

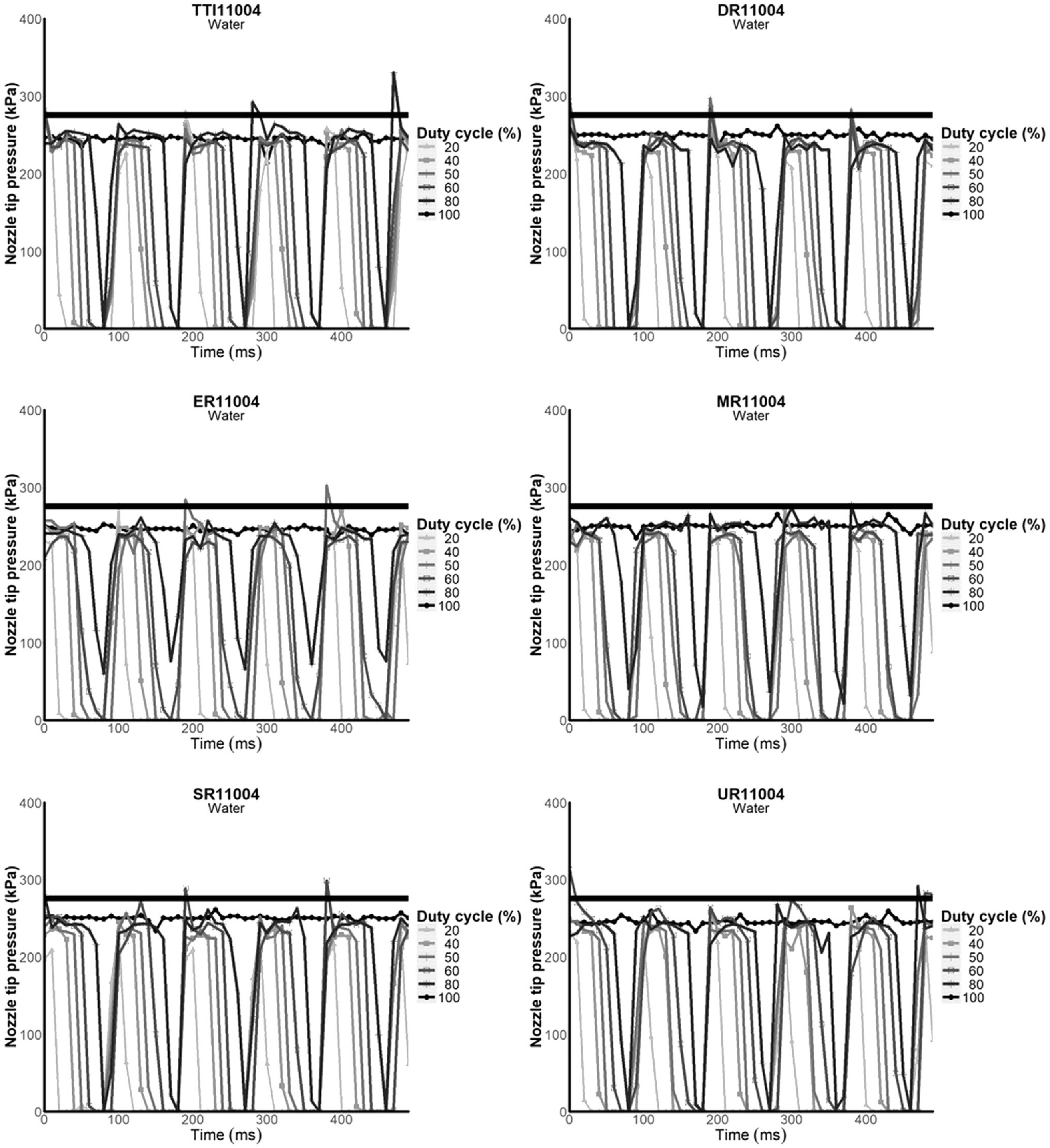

Fig. 6 – Fluctuations in nozzle tip pressure (kPa) over 0.5 s for a gauge pressure of 276 kPa with water spray solution as influenced by duty cycle for the TTI11004 (top left), DR11004 (top right), ER11004 (middle left), MR11004 (middle right), SR11004 (bottom left), and UR11004 (bottom right) nozzles. The solid black bar indicates the 276 kPa gauge pressure.

nozzle droplet size distributions fluctuated when pulsed, but not as great as the venturi nozzles, as the $D_{v0.9}$ values ranged from a decrease of 3.1% to an increase of 23.6% when the duty cycle was reduced from 100 to 40%. The driftable fines were reduced by 0.0–3.2 percentage points across non-venturi nozzles and within gauge pressures as the duty cycle decreased from 100 to 40% indicating the pulsing of PWM sprayers can reduce particle drift potential. Overall, droplet size distributions from non-venturi nozzles were more stable and homogenous when pulsed compared to venturi nozzles,

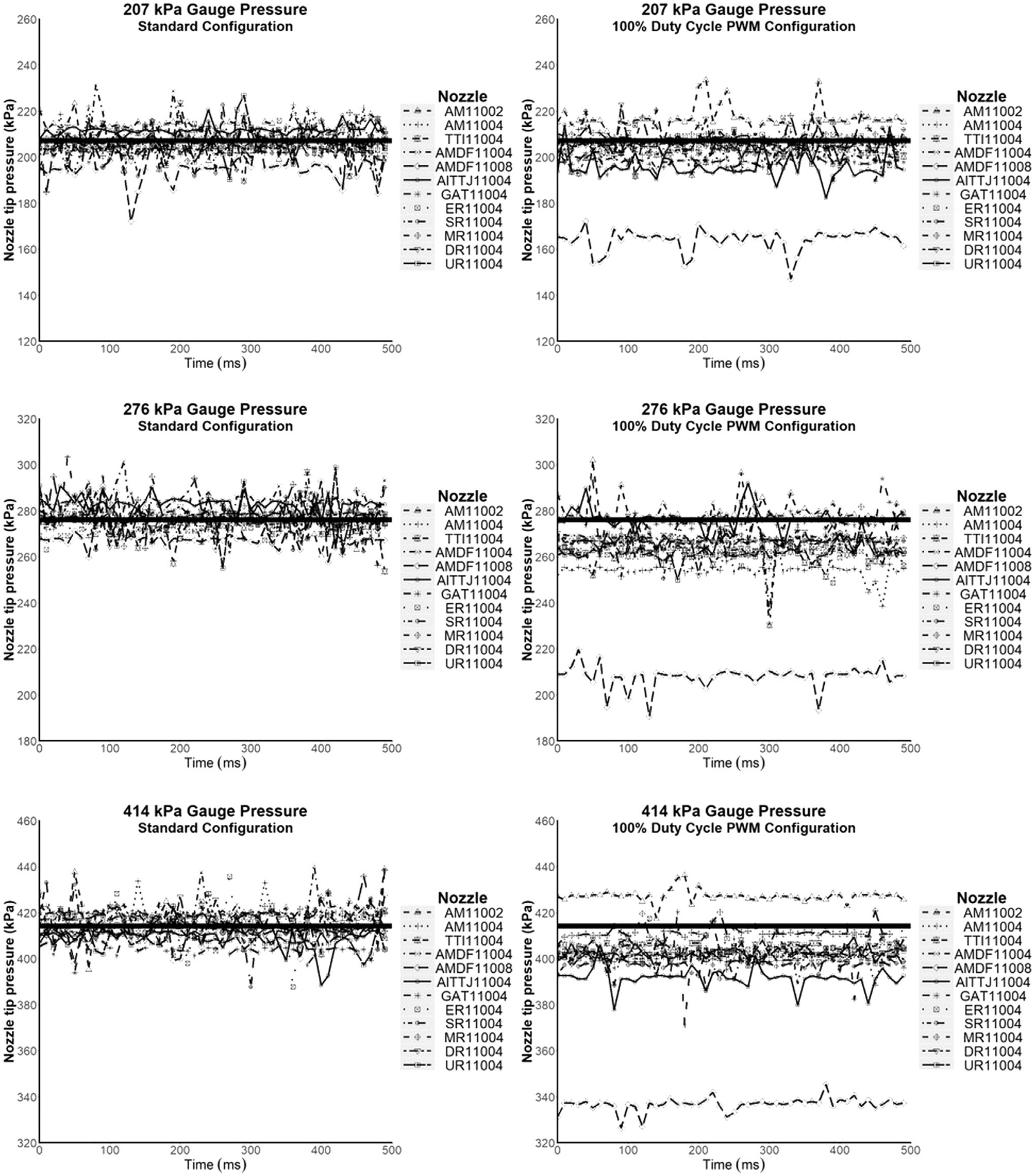

Fig. 7 – Nozzle tip pressure of 12 nozzles when spraying water in a standard nozzle body configuration (no solenoid valve) at 207 kPa (top left), 276 kPa (middle left), and 414 kPa (bottom left) and at a 100% duty cycle in a pulsing nozzle body configuration (with solenoid valve) at 207 kPa (top right), 276 kPa (middle right), and 414 kPa (bottom right). The solid black bar indicates the respective gauge pressure.

and the addition of a pre-orifice had little to no impact on the droplet size trends observed across PWM duty cycles. Therefore, non-venturi nozzles with or without pre-orifices are recommended for use on PWM sprayers to stabilize droplet size distributions across a range of duty cycles, and a 40% duty cycle or greater should be utilized to optimize and homogenize PWM pesticide applications, especially for site-specific pest management strategies requiring an explicit droplet size.

3.2. *Nozzle tip pressure*

Visual assessments of nozzle tip pressure patterns across duty cycles revealed minimal deviations from the square wave PWM electrical signal pattern due to gauge pressure changes. Nozzle tip pressure measurements over time at the 276 kPa gauge pressure are presented in Figs. 5 and 6. They illustrate PWM duty cycles operating at the 10 Hz frequency and that nozzle tip pressures do not follow the square wave electrical signal pattern explicitly, especially across nozzle types (Figs. 5 and 6). Some of the pressure measurement variability can be attributed to the single nozzle/spray solution supply line used for testing (Fig. 1). Commercial systems buffer this effect by placing multiple solenoid valves, operating on alternate frequencies, on a similar supply line or boom section (Mangus et al., 2017). Nozzle tip pressure peaks and valleys emerged for venturi nozzles, excluding the AMDF11008 and TTI11004, compared to non-venturi nozzles. Additionally, the AITTJ-6011004 and GAT11004 venturi nozzles had severe deformities in nozzle tip pressure measurement patterns when pulsed. This is likely due to the nozzle design of each as the AITTJ-6011004 and GAT11004 have a single pre-orifice with dual fan exit orifices which is unique compared to other nozzles tested. Although these pressure fluctuation deformities did not influence droplet size to a great extent, spray pattern could be highly affected, and should be evaluated in future research.

The average nozzle tip pressure measurement trends across duty cycle were unaffected by gauge pressure (Table 7). Nozzle design and orifice size impacted the nozzle tip pressure measurements across gauge pressures and duty cycles. When the PWM duty cycle was reduced from 100% to a specific duty cycle, the average nozzle tip pressure reduction should have been equivalent to the duty cycle reduction (i.e. if the duty cycle were reduced from 100 to 50%, the average nozzle tip pressure at the 50% duty cycle should be half of the nozzle tip pressure at the 100% duty cycle). When nozzle orifice size decreased (AM11002), the percent change in average nozzle tip pressure was less than expected (54%) across gauge pressures if duty cycle was reduced by 60%. In contrast, when nozzle orifice size increased (AMDF11008), the percent change in average nozzle tip pressure was greater than expected (64%) across gauge pressures if duty cycle was reduced by 60%. The AITTJ-6011004 and GAT11004 nozzles again had larger disturbances in their nozzle tip pressure patterns compared to other nozzles. The percent change in average nozzle tip pressure for the AITTJ-6011004 and GAT11004 was greater than expected, 66% for both nozzles across gauge pressures, if duty cycle was reduced by 60%. Other nozzles tested had a percent change in average nozzle tip pressure of 60% across gauge pressures if duty cycle was reduced 60%.

Measurements further revealed a reduction in nozzle tip pressure as orifice size increased and when the dual fan, single pre-orifice venturi nozzles (AITTJ-6011004 and GAT11004) were equipped and operated at a 100% duty cycle compared to a standard configuration with no solenoid valve equipped (Fig. 7). The AITTJ-6011004, AMDF11008, and GAT11004 had the lowest average nozzle tip pressures and the AM11002 had the greatest average nozzle tip pressure compared to other nozzles across gauge pressures when a solenoid valve was equipped. The greatest pressure reduction observed was for the AMDF11008 which had a loss in pressure of nearly 75 kPa. These pressure losses are likely produced by a restriction within the solenoid valve; therefore, maximum flow is restricted especially with greater orifice sizes (flow rates), and a low pressure area is created on the exit side of the solenoid. Commercial PWM systems adjust for this pressure loss with an increase in calculated duty cycle to maintain the appropriate output. However, applicators should make note of this pressure loss, as several negative impacts may arise from this finding: (1) the reduced pressure at the nozzle increases droplet size compared to what would be expected from the input gauge pressure, and reductions in biological efficacy may occur, especially in droplet size oriented site-specific pest management strategies; (2) if PWM sprayers were operated at low gauge pressures, the pressure loss may result in nozzles being operated below nozzle manufacturer's recommended pressure ranges; and (3) the reduced nozzle pressure may lead to incomplete pattern formation, especially when pulsed, resulting in reduced efficacy and inefficient applications.

4. Conclusions

The effectiveness of site-specific pest management strategies relies on two factors, (1) maximizing the biological effect, and (2) minimizing environmental contamination through off-target spray movement. Spray droplet size is a critical component to influence these two factors simultaneously. If spray droplet size is to be optimized and homogenized across a PWM application, the following best use practices should be followed:

1. PWM sprayers should be operated at or above a 40% duty cycle. Droplet size was severely affected and the pattern of change was inconsistent when pulsed at the 20% duty cycle tested in this research.
2. PWM sprayers should be operated at or above 276 kPa gauge pressure. This practice buffers the pulsing impact on droplet size and remains above nozzle manufacturers' recommended pressures due to the pressure loss across the solenoid valve.
3. Only non-venturi nozzles should be equipped and operated on PWM sprayers. These nozzle types, with and without pre-orifices, minimize variation in droplet size and nozzle tip pressure across duty cycles compared with venturi nozzles.

Applicators using a PWM sprayer should also acknowledge the pressure loss across the solenoid valve. The decreased pressure, especially for greater orifice size nozzles, could affect spray pattern and create coarser droplet sizes than desired for biological control. Further, as PWM duty cycle decreases, spray droplet size increases, thereby potentially impacting spray coverage and the resulting biological efficacy. Across non-venturi nozzles and gauge pressures, droplet size ($D_{v0.5}$) increased by approximately 0.55 μm for every 1% decrease in duty cycle. Spray solution changed the overall droplet sizes observed; however, the effect of pulsing had little to no impact on the droplet size trends observed across duty cycles for the solutions tested. Through these practices, applicators can increase the efficiency of PWM pesticide applications and reduce the risks of off-target spray particle movement by better understanding the complexities of spray applications.

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