

Nozzle Tip Selection for Pulse Width Modulated (PWM) Sprayers

Introduction

Self-propelled sprayers are commonly equipped with flow-based liquid control systems. The commercial sprayers use fixed-orifice nozzles, which are selected according to product label specifications including application rate, speed of travel, and droplet size spectrum. During typical field operation, the operator usually changes the application speed to maneuver around field obstacles, implement turns after each pass, or to cover more area in a productive manner. During these events, the flow-based rate controller varies the flowrate and the number of actuated boom and control sections to maintain the target application rate. As the control system manages the flowrate, the pressure across the nozzles invariably increases and decreases with the flow rate changes, potentially impacting the droplet size (higher driftable fines or coarser droplets) distribution and the spray coverage. Previous research has shown that in a flow-based system, the nozzle pressure variations ranged from 7% to 20% beyond the target, during section control actuation (Sharda et al., 2013). All such real-world operating instances have the potential to deviate droplet size distribution and impact spray coverage uniformity when using flow-based controllers with wider speed variations.

One of the technologies currently implemented in agricultural sprayers is Pulse Width Modulation (PWM). In this system, flow is varied by pulsing an electronically actuated solenoid valve that is directly situated before the nozzle by changing the duty cycle (Figure 1) during speed transition, while the system, presumably, tries to maintain target application pressure at all times. Flow control actuation at the solenoid level maintains full pressure in the booms when the solenoid valves are in the OFF state, and can rapidly provide target pressure with fully developed spray fan patterns when the system cycles back to the ON state.



Figure 1. Solenoid valve mounted on the nozzle body to apply the product based on PWM

Laboratory experiments at Kansas State University have shown that a PWM system can potentially maintain application pressures within a 5% error range irrespective of section control actuation (Figure 2) (Mangus et al., 2015). At a constant application pressure, the duty cycle has no significant effect on the spray droplet size when using non-venturi nozzles and nozzles without a pre-orifice (Giles et al., 1996). The PWM systems are capable and have been demonstrated to operate between 10% and 100% duty cycles. However, operators may wish to maintain nozzle duty cycle between 50% and 100% in order to achieve greater spray coverage uniformity (Mangus et al., 2015).

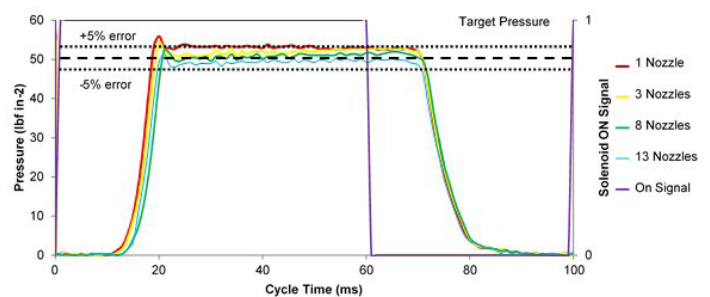


Figure 2. Operating pressure was within $\pm 5\%$ of the 50-psi target pressure when operating at 60% duty cycle regardless of section control actuation when using a PWM system.

In realistic field operating conditions, operators would experience wide speed ranges, including instances where the sprayer has to be driven at relatively slower speeds requiring lower duty cycles.

The droplet size, velocity distribution, and volume distribution pattern, are some of the spray characteristics that have a potential influence on the efficiency of pesticide application (Miller et al., 2000). Therefore, it is important to select the correct nozzle, pressure, and rate control system that can manage the droplet size distribution and spray coverage to maximize the spray efficiency and minimize the off-target losses.

Nozzle Orifice Size Selection

Nozzle size selection for PWM sprayer is similar to nozzle selection as a standard sprayer however, it requires additional careful considerations. Nozzle selection for a PWM spray applicator is done considering product label specification (application pressure, target droplet size), operator driving style (most commonly intended ground speed), and machine operating requirements (significant spray time with target duty cycle range from 50% to 100%). The nozzle orifice selection process also outlines driving speed ranges. Once the operator makes a selection on nozzle orifice, field operation should preferably be conducted within established speed ranges to implement spray application within target duty cycles. Operating sprayers at speeds lower than the target speed range can potentially result in duty cycles less than the targeted one, impacting coverage (Mangus et al., 2015) while speed beyond the maximum established speed can result in application rate errors (under-application).

The following three case scenarios show the step-by-step process that could be used for selecting a tip orifice. These case scenarios have also been presented to show the effect of selecting a preferred speed and duty cycle on nozzle orifice size selection.

Case 1: Operator selects to apply the product at the rate of 12 gallons per acre (GPA) at an intended speed of 12 mph. The selected nozzle should be able to produce medium droplet size as per label requirement. The desired duty cycle during 12 mph operation is 80%.

STEP-1: Determine the appropriate nozzle size.

$$GPM = \frac{(GPA)(nsi)(mph)}{5940}$$

Where:

GPM= nozzle flowrate, gallons per minute

GPA = desired application rate, GPA

nsi = nozzle spacing, inches

mph = preferred sprayer speed, miles per hour

Conventional nozzle size needed

$$GPM = \frac{(12)(20)(12)}{5940} = 0.48 \text{ GPM}$$

STEP-2: Operator needs to establish a most desirable duty cycle for spraying because it plays an important role in identifying the speed range for a particular nozzle orifice size.

Target nozzle size appropriate to deliver 0.48 GPM at 80% DC.

$$\text{Nozzle Size/Capacity} = GPM/(DC/100)$$

where;

GPM = nozzle flowrate, GPM

DC = desired duty cycle, %

$$\text{Nozzle Size/Capacity} = (0.48)/(80/100) = 0.61 \text{ GPM}$$

If the operator selects an 06 nozzle

Target application pressure = 40 psi

The flow rate from 06 nozzle at target application pressure of 40 psi = 0.6 GPM

Speed at 100% Duty Cycle:

$$mph = \frac{(GPM)(5940)}{(NSI)(GPA)} = \frac{(0.6)(5940)}{(20)(12)} = 14.9$$

Speed at 50% Duty Cycle: MPH = 14.9 × 0.5 = 7.4

Case 2: Operator will be applying 12 GPA of product at an intended speed of 15 mph.

Case 3: Operator opted to operate at 15 mph to apply product at the rate of 12 GPA with the desired duty cycle of 70%

For all these scenarios, a 120-ft boom sprayer with 73 – XR Teejet nozzle tips (Figure 3) spaced at 20 inches apart with application pressure of 40psi is used.

Table 1 shows various metrics and options on nozzle orifice selection and operating speeds for all cases. Operator who opted to operate based on the conditions presented for Case 1, the expected nozzle flowrate is 0.61 GPM at 100% duty cycle. Selection of 06-nozzle orifice size can be used to deliver the desired application rate and operator might try to operate within a range of 7.4 mph (50% duty cycle) up to 14.9 mph (100% duty cycle) for majority of the time. For Case 2, the target operating speed was increased to 15 mph. The selected parameters provided the expected flow rate to be 0.76 GPM and selection of 08 nozzle (0.8 GPM) nozzle orifice can provide speed ranging from 9.9 mph (50% duty cycle) to 19.8 mph 100% duty cycle). It should be noted that for both Case 1 and Case 2, the operator's application rate is 12 GPA and calculated nozzle

flow rate for PWM system is 0.61 GPM and 0.76 GPM respectively. However, selecting a smaller nozzle orifice size, as in Case 1, will provide the operator the flexibility to operate at a slower speed but it will limit the sprayer top speed. The 06 option can be advantageous when conducting application in fields with irregular shapes; varying terrain including terraces, waterways, and hills; and rough fields which requires slowing down for ditches, badger holes, and tire tracks from working in a field when it is too wet. Conversely, selecting a 08 nozzle orifice as in Case 2 will provide the operator the ability to spray at a higher speed while restricting the minimum speed range. This could be beneficial for more rectangular-shaped fields with relatively flat terrain wherein an operator expects to have more opportunity to gain high operating speeds to cover more acres in a productive manner.

Case 3 provides an example which compares nozzle selection when selecting a lower target duty cycle of 70% compared to 80% in Case 2. Therefore, it should be noted that opting to implement application parameters at lower duty cycle would need a bigger nozzle orifice so it can match application rates at 100% duty cycle. This case is also a classic situation where operator will have to pick an available nozzle orifice (08 or 10) since manufacturers may not have a matching nozzle (09) for the calculated flow rate at 100% duty cycle. In cases where matching nozzle is not available, selecting a bigger nozzle orifice size, as

in Case 3 would provide an operating speed advantage, while selecting of 08 tip would have provided exactly same speed range as in Case 2. It is also important to note that all the selection of nozzle orifice and operating pressure will provide medium droplet size, which was the label requirement (Figure 3). Overall, nozzle flow rate based on selected orifice size and application pressure, and application rate dictates preferable operating speed ranges for field operation.

An operator should be aware that once the selected nozzle orifice size and application rate is programmed in the rate controller, the controller manages the duty cycles based on operating speed. As an example, in Case 3, if the selected nozzle orifice size is 10, the actual duty cycle at 15 mph will be 61% ($=0.61 \times 100 / 1.0$) instead of the expected 70% due to the size of the nozzle orifice selected and application conditions. In all practical conditions, the operator would still continue to operate at duty cycles less than 50% while safely making turns on headlands and maneuvering field obstacles. However, the operator might consider operating as much within the speed range that provides duty cycles within 50% and 100% as possible for greater spray coverage.

Nozzle Orifice Size: Comparison between flow-based and PWM System

The operator should also be aware that there will be difference in nozzle orifice size with a flow-based and a PWM control system. As presented in table 1, in Case 1, there is a 50% increase in nozzle orifice size when moving from a flow-based system to a PWM system. In case 2 and Case 3, the increase in the nozzle orifice size is 33.3% and 66.7% respectively when transitioning to the PWM system. Overall, there is a slight increase in orifice size when implementing a PWM system, but as evident from Table 1, the operator can expect to gain wider speed range to conduct spray application, with advantages of consistent pressure and droplet size that come along with using the PWM technology.

Final Thoughts

The demand for the use of PWM technology in agricultural sprayers continues to increase because of its ability to provide more consistent spray pressure over a wide range of operating speeds. It is important, however, for operators to follow the recommendations of the pesticide companies in terms of nozzle size, droplet spectra, and travel speed, and spray nozzle manufacturer in terms of nozzle spacing and boom height when using a PWM system. These parameters are crucial in attaining the desired droplet size and proper nozzle overlap during application.

Coverage uniformities can be enhanced and application errors can be reduced by operating at a speed that needs

Table 1. Nozzle orifice size, actual application duty cycle, maximum and minimum speed of sprayer when operating at the three case scenarios.

Inputs	Case 1	Case 2	Case 3
Application rate, GPA	12	12	12
Target speed, mph	12	15	15
Desired duty cycle, %	80	80	70
Minimum Acceptable Duty Cycle, %	50	50	50
Application pressure, psi	40	40	40
Nozzle spacing, in	20	20	20
Flow-Based System			
Nozzle flowrate, at target speed	0.48	0.61	0.61
Nozzle orifice size selected	04	06	06
PWM System			
Nozzle flowrate at target speed and desired duty cycle, GPM	0.48	0.61	0.61
Nozzle flowrate at 100% duty cycle, GPM	0.61	0.76	0.87
Nozzle orifice size selected, GPM (PWM)	06	08	10
Speed at 100% duty cycle, mph	14.9	19.8	24.3
Speed at 50% duty cycle, mph	7.4	9.9	12.1
Nozzle Orifice Comparison Between Flow-based and PWM System			
Percent increased on nozzle orifice size between flow-based and PWM system, %	50.0	33.3	66.7

Nozzle Tip	PSI	DROP SIZE		CAPACITY ONE NOZZLE IN GPM	CAPACITY ONE NOZZLE IN OZ./MIN.	GPA										GALLONS PER 1000 SQ. FT.				
		80°	110°			4 MPH	5 MPH	6 MPH	8 MPH	10 MPH	12 MPH	15 MPH	20 MPH	2 MPH	3 MPH	4 MPH	5 MPH			
		20"																		
XR8001 XR11001 (100)	15	F	F	0.061	7.8	4.5	3.6	3.0	2.3	1.8	1.5	1.2	0.91	0.21	0.14	0.10	0.08			
	20	F	F	0.071	9.1	5.3	4.2	3.5	2.6	2.1	1.8	1.4	1.1	0.24	0.16	0.12	0.10			
	30	F	F	0.087	11	6.5	5.2	4.3	3.2	2.6	2.2	1.7	1.3	0.30	0.20	0.15	0.12			
	40	F	F	0.10	13	7.4	5.9	5.0	3.7	3.0	2.5	2.0	1.5	0.34	0.23	0.17	0.14			
	50	F	F	0.11	14	8.2	6.5	5.4	4.1	3.3	2.7	2.2	1.6	0.37	0.25	0.19	0.15			
60	F	VF	0.12	15	8.9	7.1	5.9	4.5	3.6	3.0	2.4	1.8	0.41	0.27	0.20	0.16				
XR80015 XR110015 (100)	15	M	F	0.092	12	6.8	5.5	4.6	3.4	2.7	2.3	1.8	1.4	0.31	0.21	0.16	0.13			
	20	F	F	0.11	14	8.2	6.5	5.4	4.1	3.3	2.7	2.2	1.6	0.37	0.25	0.19	0.15			
	30	F	F	0.13	17	9.7	7.7	6.4	4.8	3.9	3.2	2.6	1.9	0.44	0.29	0.22	0.18			
	40	F	F	0.15	19	11.1	8.9	7.4	5.6	4.5	3.7	3.0	2.2	0.51	0.34	0.26	0.20			
	50	F	F	0.17	22	12.6	10.1	8.4	6.3	5.0	4.2	3.4	2.5	0.58	0.39	0.29	0.23			
60	F	F	0.18	23	13.4	10.7	8.9	6.7	5.3	4.5	3.6	2.7	0.61	0.41	0.31	0.24				
XR8002 XR11002 (50)	15	M	M	0.12	15	8.9	7.1	5.9	4.5	3.6	3.0	2.4	1.8	0.41	0.27	0.20	0.16			
	20	M	F	0.14	18	10.4	8.3	6.9	5.2	4.2	3.5	2.8	2.1	0.48	0.32	0.24	0.19			
	30	F	F	0.17	22	12.6	10.1	8.4	6.3	5.0	4.2	3.4	2.5	0.58	0.39	0.29	0.23			
	40	F	F	0.20	26	14.9	11.9	9.9	7.4	5.9	5.0	4.0	3.0	0.68	0.45	0.34	0.27			
	50	F	F	0.22	28	16.3	13.1	10.9	8.2	6.5	5.4	4.4	3.3	0.75	0.50	0.37	0.30			
60	F	F	0.24	31	17.8	14.3	11.9	8.9	7.1	5.9	4.8	3.6	0.82	0.54	0.41	0.33				
XR80025 XR110025 (50)	15	M	M	0.15	19	11.1	8.9	7.4	5.6	4.5	3.7	3.0	2.2	0.51	0.34	0.26	0.20			
	20	M	M	0.18	23	13.4	10.7	8.9	6.7	5.3	4.5	3.6	2.7	0.61	0.41	0.31	0.24			
	30	F	F	0.22	28	16.3	13.1	10.9	8.2	6.5	5.4	4.4	3.3	0.75	0.50	0.37	0.30			
	40	F	F	0.25	32	18.6	14.9	12.4	9.3	7.4	6.2	5.0	3.7	0.85	0.57	0.43	0.34			
	50	F	F	0.28	36	21	16.6	13.9	10.4	8.3	6.9	5.5	4.2	0.95	0.63	0.48	0.38			
60	F	F	0.31	40	23	18.4	15.3	11.5	9.2	7.7	6.1	4.6	1.1	0.70	0.53	0.42				
XR8003 XR11003 (50)	15	M	M	0.18	23	13.4	10.7	8.9	6.7	5.3	4.5	3.6	2.7	0.61	0.41	0.31	0.24			
	20	M	M	0.21	27	15.6	12.5	10.4	7.8	6.2	5.2	4.2	3.1	0.71	0.48	0.36	0.29			
	30	F	F	0.26	33	19.3	15.4	12.9	9.7	7.7	6.4	5.1	3.9	0.88	0.59	0.44	0.35			
	40	F	F	0.30	38	22	17.8	14.9	11.1	8.9	7.4	5.9	4.5	1.0	0.68	0.51	0.41			
	50	F	F	0.34	44	25	20	16.8	12.6	10.1	8.4	6.7	5.0	1.2	0.77	0.58	0.46			
60	F	F	0.37	47	27	22	18.3	13.7	11.0	9.2	7.3	5.5	1.3	0.84	0.63	0.50				
XR80035 (50)	15	M	M	0.21	27	15.6	12.5	10.4	7.8	6.2	5.2	4.2	3.1	0.71	0.48	0.36	0.29			
	20	M	M	0.25	32	18.6	14.9	12.4	9.3	7.4	6.2	5.0	3.7	0.85	0.57	0.43	0.34			
	30	M	M	0.30	38	22	17.8	14.9	11.1	8.9	7.4	5.9	4.5	1.0	0.68	0.51	0.41			
	40	M	M	0.35	45	26	21	17.3	13.0	10.4	8.7	6.9	5.2	1.2	0.79	0.60	0.48			
	50	F	F	0.39	50	29	23	19.3	14.5	11.6	9.7	7.7	5.8	1.3	0.88	0.66	0.53			
60	F	F	0.43	55	32	26	21	16.0	12.8	10.6	8.5	6.4	1.5	0.97	0.73	0.58				
XR8004 XR11004 (50)	15	C	M	0.24	31	17.8	14.3	11.9	8.9	7.1	5.9	4.8	3.6	0.82	0.54	0.41	0.33			
	20	M	M	0.28	36	21	16.6	13.9	10.4	8.3	6.9	5.5	4.2	1.0	0.63	0.48	0.38			
	30	M	M	0.35	45	26	21	17.3	13.0	10.4	8.7	6.9	5.2	1.2	0.79	0.60	0.48			
	40	M	M	0.40	51	30	24	19.8	14.9	11.9	9.9	7.9	5.9	1.4	0.91	0.68	0.54			
	50	F	F	0.45	58	33	27	22	16.7	13.4	11.1	8.9	6.7	1.5	1.0	0.77	0.61			
60	F	F	0.49	63	36	29	24	18.2	14.6	12.1	9.7	7.3	1.7	1.1	0.83	0.67				
XR8005 XR11005 (50)	15	C	M	0.31	40	23	18.4	15.3	11.5	9.2	7.7	6.1	4.6	1.1	0.70	0.53	0.42			
	20	C	M	0.35	45	26	21	17.3	13.0	10.4	8.7	6.9	5.2	1.2	0.79	0.60	0.48			
	30	M	M	0.43	55	32	26	21	16.0	12.8	10.6	8.5	6.4	1.5	0.97	0.73	0.58			
	40	M	M	0.50	64	37	30	25	18.6	14.9	12.4	9.9	7.4	1.7	1.1	0.85	0.68			
	50	M	F	0.56	72	42	33	28	21	16.6	13.9	11.1	8.3	1.9	1.3	0.95	0.76			
60	F	F	0.61	78	45	36	30	23	18.1	15.1	12.1	9.1	2.1	1.4	1.0	0.83				
XR8006 XR11006 (50)	15	C	C	0.37	47	27	22	18.3	13.7	11.0	9.2	7.3	5.5	1.3	0.84	0.63	0.50			
	20	C	M	0.42	54	31	25	21	15.6	12.5	10.4	8.3	6.2	1.4	1.0	0.71	0.57			
	30	M	M	0.52	67	39	31	26	19.3	15.4	12.9	10.3	7.7	1.8	1.2	0.88	0.71			
	40	M	M	0.60	77	45	36	30	22	17.8	14.9	11.9	8.9	2.0	1.4	1.0	0.82			
	50	M	M	0.67	86	50	40	33	25	19.9	16.6	13.3	9.9	2.3	1.5	1.1	0.91			
60	M	F	0.73	93	54	43	36	27	22	18.1	14.5	10.8	2.5	1.7	1.2	0.99				
XR8008 XR11008 (50)	15	VC	C	0.49	63	36	29	24	18.2	14.6	12.1	9.7	7.3	1.7	1.1	0.83	0.67			
	20	VC	C	0.57	73	42	34	28	21	16.9	14.1	11.3	8.5	1.9	1.3	0.97	0.78			
	30	C	C	0.69	88	51	41	34	26	20	17.1	13.7	10.2	2.3	1.6	1.2	0.94			
	40	M	M	0.80	102	59	48	40	30	24	19.8	15.8	11.9	2.7	1.8	1.4	1.1			
	50	M	M	0.89	114	66	53	44	33	26	22	17.6	13.2	3.0	2.0	1.5	1.2			
60	M	M	0.98	125	73	58	49	36	29	24	19.4	14.6	3.3	2.2	1.7	1.3				
XR8010 [†] XR11010 [†]	15	XC	VC	0.61	78	45	36	30	23	18.1	15.1	12.1	9.1	2.1	1.4	1.0	0.83			
	20	VC	C	0.71	91	53	42	35	26	21	17.6	14.1	10.5	2.4	1.6	1.2	0.97			
	30	C	C	0.87	111	65	52	43	32	26	22	17.2	12.9	3.0	2.0	1.5	1.2			
	40	C	M	1.00	128	74	59	50	37	30	25	19.8	14.9	3.4	2.3	1.7	1.4			
	50	M	M	1.12	143	83	67	55	42	33	28	22	16.6	3.8	2.5	1.9	1.5			
60	C	M	1.22	156	91	72	60	45	36	30	24	18.1	4.1	2.8	2.1	1.7				
XR8015 [†] XR11015 [†]	15	XC	VC	0.92	118	68	55	46	34	27	23	18.2	13.7	3.1	2.1	1.6	1.3			
	20	XC	VC	1.06	136	79	63	52	39	31	26	21	15.7	3.6	2.4	1.8	1.4			
	30	VC	VC	1.30	166	97	77	64	48	39	32	26	19.3	4.4	2.9	2.2	1.8			
	40	VC	C	1.50	192	111	89	74	56	45	37	30	22	5.1	3.4	2.6	2.0			
	50	C	C	1.68	215	125	100	83	62	50	42	33	25	5.7	3.8	2.9	2.3			
60	C	C	1.84	236	137	109	91	68	55	46	36	27	6.3	4.2	3.1	2.5				

Figure 3. Recommended typical applications for XR Teejet Nozzle tips (Teejet Technologies, 2014)

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duty cycles greater than 50% and selecting the appropriate nozzle size based on the desired application rate, pressure, and droplet spectra.

References