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RESEARCH ARTICLE

Effect of Swirl Plates on Volumetric Discharge Rate and Spray Characteristics of Hollow Cone Nozzles

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ABSTRACT

The aim of the study is to determine the effect of orifice diameter, swirl plate and spray pressure on the volumetric flow, discharge coefficient and some spray characteristics of hollow cone nozzles. In the trials, five nozzle discs with 1,0, 1,2, 1,6, 2,0 and 2,4 millimetres orifice diameters and three polyacetal materials with 2 or 3 slots and one stainless steel with 2-slots swirl plate were used. Spray application were made at spray pressures of 2, 4, 6, 8 and 12 bar. The highest discharge rate at constant pressure was obtained with stainless steel and the lowest blue swirl plates. Although the number of slots was different, the effect of brown and yellow swirl plates on volumetric discharge rate variation was statistically insignificant. The discharge coefficient decreased as the diameter of the nozzle orifice increased. Accordingly, the average discharge coefficient for the 1,0 mm, 1,2, 1,6, 2,0 and 2,4 mm diameter nozzle discs was 0,411, 0,362, 0,285, 0,236 and 0.201, respectively. It was estimated that the droplet diameter in the range of 2-12 bar in the hollow cone nozzles varied between 76,3-219,0 µm and it was determined that mostly very fine and partially fine and medium sized droplets were produced.

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Introduction

Spray characteristics in pesticide application have a significant impact on biological activity of harmful agents. Laboratory experiments have been demonstrated that droplets smaller than 100 µm are more useful in insecticides and fungicides (Matthews et al., 2014).

The transport potential of pesticides to the target in droplets, spray deposition, droplet penetration, spray coverage and drift potential depends on the droplet diameter in spray application (Bode et al., 1983; Nuyttens et al., 2007). The large or small droplets in pesticide application can limit the success of the application. The drift problem can be minimized (Bode et al., 1983) in applications with large droplets, but there may be a problem of deposition or spray coverage on the target surface (Smith et al., 2000). Because the energy of the small droplets is low, the droplets can be suspended in the air, they can evaporate before reaching the target (Bayat and Bozdoğan, 2005) or they can transport out of the target due to wind (Bode et al., 1983). For these reasons, the optimum droplet size in spray application is important in terms of the efficiency of pesticide application and environmental pollution caused by drift.

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In order to reduce pesticide losses due to drift, new spray technologies have been developing, some R&D studies on existing equipment have been carrying out and various improvements on spray technologies have been made. Some of the current developments; new generation nozzles (low drift potential, pneumatic, rotary disc, variable displacement, double slotted and multi-head nozzles, etc.), auxiliary airflow spray technologies, electrostatic charging technique, boom arm protection curtains, tunnel type atomizers, sprayers that detect plant canopy, variable-rate herbicide application technology can be listed as GPS detection of sprayer transitions, direct injection system, product tilting system and spray boom balancing systems (Dursun et al., 2000).

Despite advances in spray technologies, operators do not abandon conventional methods and prefer standard nozzles since they are cheap and easy to procure rather than new generation hydraulic nozzles. Commonly used hollow cone nozzles are in the form of disc and there is orifice with circle geometry in the centre. When the nozzle discs are used together with the swirl plate, atomization takes place. Swirl plates may affect the nozzle discharge rate and may cause a change in the spray characteristics (Sayıncı et al., 2017).

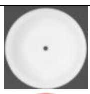
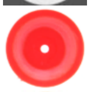
The aim of this study is to determine the effects on discharge coefficient and volumetric discharge rate variation of swirl plates slot number of which are made from different manufacturing materials, and reveal spray characteristics by estimating the droplet diameter at various operational pressure levels.

Materials and Methods

Hollow Cone Nozzles and Swirl Plates

In the experiments, hollow cone nozzle discs made of polyacetal (POM) material with orifice diameters of 1,0 mm, 1,2 mm, 1,6 mm, 2,0 mm and 2,4 mm were used. Each orifice diameter group were replicated five times. Four swirl plates having different slot number or manufacturing material were used in each nozzle disc. To ensure discrimination among the swirl plates, each plate was named according to colour codes or material, and some features were given in Table 1.

Table 1. Hollow cone nozzle discs and swirl plates

Nozzle discs		Swirl plates		
Orifice diameter (*Ød*)	Nozzle discs	Colour code/Material (Slot number, material)	Manufacturing	Swirl plates
1.0 mm		Blue (2-slot, POM*)	Imported (C23)	
1.2 mm		Brown (3-slot, POM)	Local	
1.6 mm		Yellow (2-slot, POM)	Local	
2.0 mm		Stainless steel (2 slot, SS**)	Local	
2.4 mm				

*: polyacetal; **: stainless steel

Hydraulic Pressure Unit

The hydraulic pressure was provided by a conventional sprayer with a tank capacity of 200 litres. The pressure regulator (max. 40 bar, 90 L min^{-1}, RG-7 Model) connected on the pressure line provided to be controlled of the operating pressure by a manometer (Pakkens® Model, TR) with a glycerine filling with a maximum of 25 bar display. The self-pump of the sprayer (TAR30 piston-membrane, double piston, rated nominal pressure of 40 kg cm^{-2}, rated discharge rate of 30 L min^{-1}, 67% efficiency, Taral®, TR) was used to transmit the fluid in the polyethylene tank to the spray line. In the study, the pump shaft was mounted on a belt-pulley driven mechanism which takes action of the electric motor (2,2 kW, 1405 rpm, AGM 100L 4a type, Gamak, TR). The pump shaft revolution was measured as 500 rpm using an optical tachometer (Testo 465, KGaA).

Determination of Volumetric Discharge Rate

The discharge rate was measured with a flowmeter (Sprayer Calibrator, SpotOn®, Model: SC-1, IL, measurement accuracy: ±2,5%; measuring range: 0,08-3,79 L min^{-1}) without using any filter. The measurements were replicated five times at five different spray pressures including 2 bar, 4 bar, 6 bar, 8 bar and 12 bar. Sayıncı and Kara (2015) found differences between the operational pressure measured on the regulator and the spray pressure measured from a close point to the nozzle due to the pipe loss. Therefore, the fluid pressure was controlled by a digital manometer (Ref D2, 0,1%, 0-400 bar, SICA GmbH & Co. KG) mounted at a point close to the nozzle and the measured value was referred to as the spray pressure.

In the combinations of the nozzle disc and the swirl plate, the linear variation among the discharge rate and square root of the pressure was given in the form of a [$y = ax + b$] equation. In order to test the effect of the swirl plates on the discharge rate with a common variable, the slope (*a*) of the line was determined from the [$y = ax$] equation and subjected to the analysis of variance (ANOVA). The differences between the significant averages were determined by the Tukey multiple comparison test at 95% significance level.

Sayıncı et al. (2013) stated that there was no any reference standard for the operating characteristics of the locally used hollow cone nozzles. In this study, a demonstration indicating the operational characteristics of nozzle orifices used with different swirl plates was made. Hypro® (2014) catalogue prepared according to BCPC was taken as reference and "nozzle type / discharge rate (L min^{-1}) / pressure (bar)" notation layout was used.

Determination of Discharge Coefficient

The discharge coefficient, which expressed the energy loss caused by friction in the nozzle disc and swirl plate, was calculated using Equation (1) (Srivastava et al., 1993; Ballester and Dopazo, 1994; Rashid et al., 2012; Yu et al., 2013; Sayıncı, 2016).

$$C_D = \frac{Q}{\sqrt{\Delta P}} \cdot \sqrt{\left(\frac{\rho_L}{2 \cdot A}\right)} \qquad (1)$$

C_D: discharge coefficient
Q: discharge rate (m^3 s^{-1})
ΔP: pressure (Pa)
ρ_L: liquid density (999.1 kg m^{-3}, @15 °C liquid temperature)
A: orifice area (m^2)

One-way analysis of variance (ANOVA) was performed to test the effect of the swirl plate on the discharge coefficient in the nozzle orifice groups. The difference between the significant averages was determined by the Tukey test at 95% significance level.

Droplet Size ($D_{V0.50}$)

The droplet diameter was estimated using Equation (2) in nozzle disc and swirl plate combinations with different spray pressures (Iqbal et al., 2005).

$$D_{V0.50} = 437 \cdot \sqrt[3]{\frac{k}{\Delta P}} \qquad (2)$$

$D_{V0.50}$: droplet diameter (µm)
k: orifice coefficient ($k=q/\sqrt{\Delta P}$)
ΔP: pressure (psi)
q: discharge rate (gal h^{-1})

The droplet diameter classes have been classified into eight categories according to ASABE S572.1 standard (ASABE, 2009) as shown in Table 2, and the diameter categories have been standardized according to their colours respectively in purple, red, orange, yellow, blue, green, white and black. According to this standard, many researchers used different reference ranges for droplet diameter in spray categories. In this study, the droplet diameter colour category of nozzle orifices determined according to the diameter ranges specified Kruger et al. (2013) and Arag® (2017) catalogue.

Table 2. Droplet size ($D_{V0.50}$, µm) categories (classification according to ASABE S572.1 standard) (ASABE, 2009)

Droplet sizes categories	$D_{V0.50}$ (µm) ranges							Droplet sizes colour categories
	Hypro® (2014)	Hipkins and Grisso (2014)	Hypropumps (2006)	Spandl (2010)	Wolf (2017)	Kruger et al.(2013); Arag® (2004)	Matthews et al. (2014)	
Extremely fine (XF)	60 <	60 <	-	50 <	-	~ 50	50 <	Purple
Very fine (VF)	61-105	60-145	100 <	51-145	150 <	136 <	51-100	Red
Fine (F)	106-235	145-225	100-175	145-225	151-250	136-177	101-200	Orange
Medium (M)	236-340	226-325	175-250	226-325	251-350	177-218	201-300	Yellow
Coarse (C)	341-403	326-400	250-375	326-400	351-450	218-349	> 300	Blue
Very coarse (VC)	404-502	401-500	375-450	401-500	451-550	349-428	-	Green
Extremely coarse (XC)	503-665	501-650	> 450	501-660	> 551	428-622	-	White
Ultra coarse (UC)	> 665	> 650	-	> 661	-	> 622	-	Black

Results

Effect of Swirl Plate on Discharge Rate Variation

Linear equations between discharge rate and pressure variables were given in Table 3. In reference to variance analysis, the effect of the swirl plate on discharge rate was found to be very significant. In the same orifice, the highest discharge rate was obtained by stainless steel and the lowest blue swirl plate. Although the number of slot on swirl plate was different, no significant difference was found between brown and yellow plates. The effect of brown, yellow and stainless steel swirl plates on the nozzle disc with an orifice diameter of 2.4 mm was found insignificant and the lowest discharge rate was obtained with a blue plate. The BCPC reference display was taken notice for the presentation of discharge rates of the nozzle discs with different swirl plates at 3 bar pressure.

Factors Affecting Discharge Coefficient

The discharge coefficient of the nozzle discs with an orifice diameter of 1,0 mm, 1,2 mm, 1,6 mm, 2,0 mm and 2,4 mm was determined as 0,411, 0,362, 0,285, 0,236 and 0,201, respectively (Figure 1). According to this result, the discharge coefficient decreased as the orifice diameter of the hollow cone nozzles increased. The swirl plates changed significantly the discharge coefficient of the nozzle (Table 4). The blue swirl plate had the lowest discharge coefficient. The highest coefficient was found at stainless steel swirl plate. The difference between the average discharge coefficients of the brown and yellow plates was mostly insignificant.

Table 3. Effect of swirl plates on nozzle discharge rate (q, L min^{-1})

Orifice diameter (mm)	Swirl plates	[1]Linear equations ($y = ax + b$)	R^2 (Corrected)	[2]Slope ($y = ax$)	F value (p, sigma)	[3]BCPC code
Ø1.0	Blue (2-slot, C23)	$y = 0{,}214x + 0{,}036$	0,997	0,228±0,003 c*	42,91	KH/0.41/3
	Brown (3-slot)	$y = 0{,}273x + 0{,}009$	0,961	0,276±0,016 b	(0,000)**	KH/0.48/3
	Yellow (2-slot)	$y = 0{,}268x + 0{,}032$	0,973	0,280±0,013 b		KH/0.50/3
	S. steel (2-slot)	$y = 0{,}296x + 0{,}022$	0,988	0,304±0,006 a		KH/0.53/3
Ø1.2	Blue (2-slot, C23)	$y = 0{,}262x + 0{,}045$	0,999	0,279±0,001 c	61,79	KH/0.50/3
	Brown (3-slot)	$y = 0{,}332x + 0{,}034$	0,961	0,345±0,019 b	(0,000)	KH/0.61/3
	Yellow (2-slot)	$y = 0{,}344x + 0{,}027$	0,988	0,354±0,011 b		KH/0.62/3
	S. steel (2-slot)	$y = 0{,}386x + 0{,}039$	0,969	0,401±0,018 a		KH/0.71/3
Ø1.6	Blue (2-slot, C23)	$y = 0{,}346x + 0{,}068$	0,979	0,372±0,014 c	55,46	KH/0.67/3
	Brown (3-slot)	$y = 0{,}464x + 0{,}065$	0,969	0,489±0,024 b	(0,000)	KH/0.87/3
	Yellow (2-slot)	$y = 0{,}486x + 0{,}066$	0,969	0,511±0,024 b		KH/0.91/3
	S. steel (2-slot)	$y = 0{,}602x - 0{,}094$	0,950	0,566±0,033 a		KH/0.95/3
Ø2.0	Blue (2-slot, C23)	$y = 0{,}448x + 0{,}051$	0,980	0,468±0,018 c	65,76	KH/0.83/3
	Brown (3-slot)	$y = 0{,}635x + 0{,}034$	0,983	0,648±0,024 b	(0,000)	KH/1.13/3
	Yellow (2-slot)	$y = 0{,}641x + 0{,}058$	0,938	0,663±0,029 b		KH/1.17/3
	S. steel (2-slot)	$y = 0{,}765x - 0{,}075$	0,949	0,736±0,047 a		KH/1.25/3
Ø2.4	Blue (2-slot, C23)	$y = 0{,}526x + 0{,}040$	0,987	0,541±0,016 b	58,16	KH/0.95/3
	Brown (3-slot)	$y = 0{,}827x - 0{,}012$	0,939	0,823±0,063 a	(0,000)	KH/1.42/3
	Yellow (2-slot)	$y = 0{,}821x + 0{,}046$	0,959	0,839±0,046 a		KH/1.47/3
	S. steel (2-slot)	$y = 0{,}869x + 0{,}022$	0,957	0,877±0,043 a		KH/1.53/3

[1] y: nozzle discharge rate (q, L min^{-1}); a: slope of the line; x: square root of pressure ($\sqrt{P}$, bar); b: intercept
[2] In order to test the effect of swirl plates on the nozzle discharge rate, the intercept (b) was accepted as zero (0) and linear equations are obtained in the form of [$y = ax$]. y: nozzle discharge rate (q, L min^{-1}); a: slope of the line; x: square root of pressure ($\sqrt{P}$, bar) (mean±SD)
[3] The coding according to BCPC reference shows the nozzle discharge rate (L min^{-1}) at 3 bar pressure. KH: hollow cone spray nozzle (Hypro®, 2017)
* According to the Tukey multiple comparison test results, the averages shown different letters in the same column for each orifice diameter group are different at 95%; **: $p<0{,}01$ very important

Table 4. The effect of swirl plates on discharge coefficient (C_D) (mean±SD)

Orifice diameter (mm)	Swirl plates	Discharge coefficient (C_D)	F value (p, sigma)
Ø1.0	Blue (2-slot, C23)	0,346±0,008 c*	193,44
	Brown (3-slot)	0,415±0,023 b	(0,000)**
	Yellow (2-slot)	0,424±0,019 b	
	S. steel (2-slot)	0,459±0,014 a	
Ø1.2	Blue (2-slot, C23)	0,294±0,008 c	265,99
	Brown (3-slot)	0,362±0,020 b	(0,000)
	Yellow (2-slot)	0,371±0,012 b	
	S. steel (2-slot)	0,421±0,021 a	
Ø1.6	Blue (2-slot, C23)	0,221±0,009 d	240,30
	Brown (3-slot)	0,289±0,014 c	(0,000)
	Yellow (2-slot)	0,302±0,015 b	
	S. steel (2-slot)	0,329±0,019 a	
Ø2.0	Blue (2-slot, C23)	0,177±0,007 c	227,33
	Brown (3-slot)	0,244±0,009 b	(0,000)
	Yellow (2-slot)	0,250±0,017 b	
	S. steel (2-slot)	0,274±0,019 a	
Ø2.4	Blue (2-slot, C23)	0,142±0,004 c	235,63
	Brown (3-slot)	0,214±0,015 b	(0,000)
	Yellow (2-slot)	0,219±0,013 b	
	S. steel (2-slot)	0,229±0,016 a	

* According to the Tukey multiple comparison test results, the averages shown different letters in the same column for each orifice diameter group are different at 95%; ** $p<0{,}01$ very important

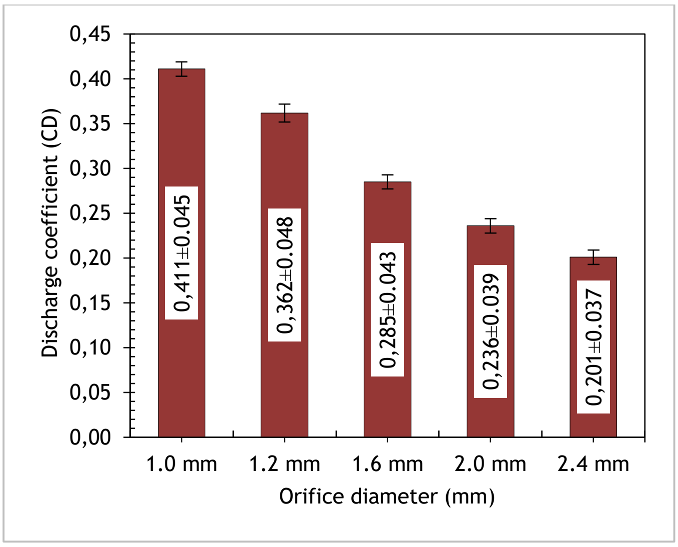


Figure 1. Discharge coefficient (mean±SD)

Droplet Size ($D_{V0.50}$)

As shown in Figure 2, the droplet diameter decreased as the spray pressure increased. While the droplet diameter averages at 2 bar spray pressure varied between 141,5-219,0 µm, the averages decreased at 12 bar and the averages ranged from 76,3 to 120,8 µm. In reference to the nozzle groups, the largest droplet diameter was obtained at 2 bar spray pressure level with the nozzle of 2.4 mm orifice diameter. As the orifice diameter increased, the droplet diameter increased. The droplet diameters obtained from the nozzles with 1,0 mm and 2,4 mm orifice diameters varied between 76,3-154,8 µm and 102,3-219,0 µm, respectively.

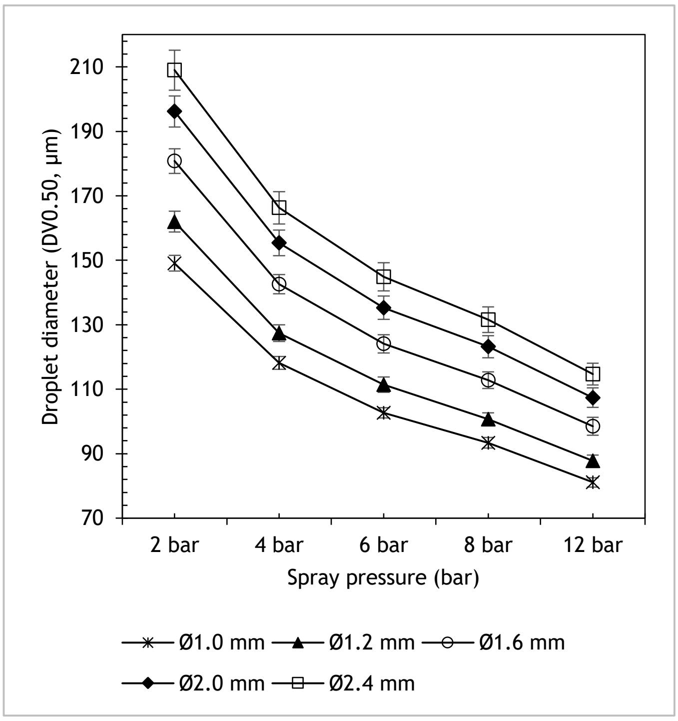


Figure 2. The variation of droplet diameter ($D_{V0.50}$, µm) according to the spray pressures for different orifice groups (mean±2·SE)

Table 5. Effect of swirl plates and spray pressures on droplet diameter ($D_{V0.50}$, µm) for the nozzle discs (mean±SD)

Orifice diameter (mm)	Swirl plates	Spray pressure				
		2 bar	4 bar	6 bar	8 bar	12 bar
Ø1.0	Blue (2-slot, C23)	141,5±0,8 c	111,9±0,7 c	97,1±0,5 c	88,2±0,4 c	76,3±0,3 c
	Brown (3-slot)	149,1±2,8 b	118,5±2,6 b	103,4±2,2 b	94,0±2,0 b	81,8±1,5 b
	Yellow (2-slot)	151,2±2,1 b	119,8±2,0 ab	103,9±1,5 ab	94,3±1,5 b	82,1±1,5 b
	S. steel (2-slot)	154,8±1,3 a	122,8±1,4 a	106,4±1,2 a	97,3±1,0 a	84,4±0,8 a
	F value (*p*, sigma)	44,64 (0,000)**	32,16 (0,000)	35,51 (0,000)	39,72 (0,000)	43,12 (0,000)
Ø1.2	Blue (2-slot, C23)	152,2±0,7 c	119,4±0,3 c	103,8±0,6 c	94,0±0,2 c	81,9±0,1 c
	Brown (3-slot)	162,0±3,3 b	127,8±2,3 b	111,7±1,9 b	100,9±2,2 b	88,0±1,7 b
	Yellow (2-slot)	163,3±1,2 b	128,5±1,7 b	112,6±1,4 b	101,9±1,0 b	88,8±0,8 b
	S. steel (2-slot)	170,7±2,3 a	133,9±2,6 a	117,4±2,1 a	106,1±1,7 a	92,5±1,6 a
	F value (*p*, sigma)	64,95 (0,000)	47,06 (0,000)	61,54 (0,000)	58,16 (0,000)	61,69 (0,000)
Ø1.6	Blue (2-slot, C23)	167,2±1,8 c	132,0±1,3 c	114,2±1,3 c	103,5±1,4 c	89,9±1,4 c
	Brown (3-slot)	182,1±3,2 b	144,0±2,3 b	125,1±1,9 b	113,7±1,8 b	98,5±1,9 b
	Yellow (2-slot)	185,1±2,9 ab	145,9±2,4 ab	126,7±2,2 b	115,7±2,1 ab	100,0±1,7 b
	S. steel (2-slot)	188,6±2,4 a	148,6±2,2 a	130,4±1,9 a	118,3±1,8 a	105,4±3,3 a
	F value (*p*, sigma)	65,85 (0,000)	62,27 (0,000)	70,24 (0,000)	64,12 (0,000)	43,06 (0,000)
Ø2.0	Blue (2-slot, C23)	179,6±1,9 b	142,0±2,3 b	123,1±1,4 c	111,7±1,4 c	97,5±1,4 c
	Brown (3-slot)	198,9±2,5 a	157,4±2,0 a	137,5±1,7 b	124,8±1,6 b	108,7±1,5 b
	Yellow (2-slot)	201,4±4,6 a	159,2±3,6 a	137,9±2,5 b	125,7±3,1 b	109,5±3,2 b
	S. steel (2-slot)	204,9±4,5 a	162,9±4,5 a	142,8±3,2 a	130,4±3,4 a	114,1±2,5 a
	F value (*p*, sigma)	49,14 (0,000)	39,35 (0,000)	67,60 (0,000)	49,55 (0,000)	48,08 (0,000)
Ø2.4	Blue (2-slot, C23)	187,6±1,7 b	148,6±1,5 b	129,3±1,3 b	117,5±1,5 b	102,3±1,1 b
	Brown (3-slot)	213,6±5,4 a	169,5±4,5 a	148,9±4,1 a	135,5±3,5 a	117,7±3,0 a
	Yellow (2-slot)	215,7±5,2 a	171,5±3,9 a	150,4±3,8 a	136,2±2,7 a	118,1±1,6 a
	S. steel (2-slot)	219,0±8,4 a	175,6±4,3 a	151,1±2,3 a	137,1±3,0 a	120,8±1,8 a
	F value (*p*, sigma)	32,23 (0,000)	51,56 (0,000)	57,83 (0,000)	56,75 (0,000)	90,83 (0,000)

* According to the Tukey multiple comparison test results, the averages shown different letters in the same column for each orifice diameter group are different at 95%; **: $p<0,01$ very important

Table 6. The results of the regression analysis between droplet diameter ($D_{V0.50}$, μm) and spray pressure (P, bar) variables, and exponential functions

Orifice diameter (mm)	Swirl plates	[1]Exponential functions	R^2 (Corrected)	Mean error squares	F value	p (sigma)
1.0	Blue (2-slot, C23)	$D_{V0,50} = 179{,}947 \cdot P^{(-0{,}344)}$	1,000	7,4E-06	30260,7	0,000**
	Brown (3-slot)	$D_{V0,50} = 188{,}254 \cdot P^{(-0{,}335)}$	1,000	2,8E-06	75060,5	0,000
	Yellow (2-slot)	$D_{V0,50} = 191{,}777 \cdot P^{(-0{,}341)}$	1,000	3,4E-06	64100,2	0,000
	S. steel (2-slot)	$D_{V0,50} = 195{,}812 \cdot P^{(-0{,}338)}$	1,000	1,3E-05	17014,0	0,000
1.2	Blue (2-slot, C23)	$D_{V0,50} = 193{,}176 \cdot P^{(-0{,}346)}$	1,000	3,0E-06	74828,9	0,000
	Brown (3-slot)	$D_{V0,50} = 205{,}129 \cdot P^{(-0{,}341)}$	1,000	2,9E-06	76421,1	0,000
	Yellow (2-slot)	$D_{V0,50} = 206{,}358 \cdot P^{(-0{,}339)}$	1,000	5,7E-06	38054,0	0,000
	S. steel (2-slot)	$D_{V0,50} = 215{,}849 \cdot P^{(-0{,}341)}$	1,000	9,9E-06	22156,5	0,000
1.6	Blue (2-slot, C23)	$D_{V0,50} = 212{,}894 \cdot P^{(-0{,}347)}$	1,000	3,8E-06	59436,6	0,000
	Brown (3-slot)	$D_{V0,50} = 231{,}167 \cdot P^{(-0{,}342)}$	1,000	4,9E-06	45389,7	0,000
	Yellow (2-slot)	$D_{V0,50} = 234{,}638 \cdot P^{(-0{,}342)}$	1,000	1,2E-05	18163,2	0,000
	S. steel (2-slot)	$D_{V0,50} = 235{,}016 \cdot P^{(-0{,}327)}$	0,998	7,8E-05	2576,0	0,000
2.0	Blue (2-slot, C23)	$D_{V0,50} = 227{,}631 \cdot P^{(-0{,}342)}$	1,000	4,2E-06	52470,7	0,000
	Brown (3-slot)	$D_{V0,50} = 251{,}223 \cdot P^{(-0{,}337)}$	1,000	7,4E-07	290127,4	0,000
	Yellow (2-slot)	$D_{V0,50} = 254{,}871 \cdot P^{(-0{,}340)}$	1,000	7,5E-06	29064,3	0,000
	S. steel (2-slot)	$D_{V0,50} = 256{,}533 \cdot P^{(-0{,}326)}$	1,000	3,4E-06	58590,3	0,000
2.4	Blue (2-slot, C23)	$D_{V0,50} = 237{,}314 \cdot P^{(-0{,}338)}$	1,000	9,9E-07	218236,0	0,000
	Brown (3-slot)	$D_{V0,50} = 268{,}783 \cdot P^{(-0{,}331)}$	1,000	1,1E-05	18819,0	0,000
	Yellow (2-slot)	$D_{V0,50} = 272{,}771 \cdot P^{(-0{,}335)}$	1,000	1,9E-05	11150,2	0,000
	S. steel (2-slot)	$D_{V0,50} = 277{,}035 \cdot P^{(-0{,}336)}$	0,999	5,4E-05	3897,2	0,000

[1] $D_{V0.50}$: droplet diameter (μm); P: spray pressure (bar); ** $p<0{,}01$ very important

Table 7. Droplet diameter ($D_{V0.50}$, μm) categories for each combination of the nozzle discs with different orifice diameter and swirl plate according to the spray pressures

Orifice diameter (mm)	Swirl plates	Spray pressure (bar)										
		2	3	4	5	6	7	8	9	10	11	12
1.0	Blue (2-slot, C23)	F[a]	VF[b]	VF	VF	VF	VF	VF	VF	VF	VF	VF
	Brown (3-slot)	F	VF	VF	VF	VF	VF	VF	VF	VF	VF	VF
	Yellow (2-slot)	F	VF	VF	VF	VF	VF	VF	VF	VF	VF	VF
	S. steel (2-slot)	F	VF	VF	VF	VF	VF	VF	VF	VF	VF	VF
1.2	Blue (2-slot, C23)	F	VF	VF	VF	VF	VF	VF	VF	VF	VF	VF
	Brown (3-slot)	F	F	VF	VF	VF	VF	VF	VF	VF	VF	VF
	Yellow (2-slot)	F	F	VF	VF	VF	VF	VF	VF	VF	VF	VF
	S. steel (2-slot)	F	F	VF	VF	VF	VF	VF	VF	VF	VF	VF
1.6	Blue (2-slot, C23)	F	F	VF	VF	VF	VF	VF	VF	VF	VF	VF
	Brown (3-slot)	M[c]	F	F	VF	VF	VF	VF	VF	VF	VF	VF
	Yellow (2-slot)	M	F	F	VF	VF	VF	VF	VF	VF	VF	VF
	S. steel (2-slot)	M	F	F	F	VF	VF	VF	VF	VF	VF	VF
2.0	Blue (2-slot, C23)	M	F	F	VF	VF	VF	VF	VF	VF	VF	VF
	Brown (3-slot)	M	F	F	F	F	VF	VF	VF	VF	VF	VF
	Yellow (2-slot)	M	F	F	F	F	VF	VF	VF	VF	VF	VF
	S. steel (2-slot)	M	M	F	F	F	F	VF	VF	VF	VF	VF
2.4	Blue (2-slot, C23)	M	F	F	F	VF	VF	VF	VF	VF	VF	VF
	Brown (3-slot)	M	M	F	F	F	F	VF	VF	VF	VF	VF
	Yellow (2-slot)	M	M	F	F	F	F	F	VF	VF	VF	VF
	S. steel (2-slot)	C[d]	M	F	F	F	F	F	VF	VF	VF	VF

[a] F, fine; [b] VF, very fine; [c] M, medium; [d] C, coarse

At the nozzle discs of 1,0 mm, 1,2 mm and 1,6 mm orifice diameters, the largest droplet diameter was obtained in the stainless steel swirl plate, the lowest blue swirl plate (Table 5). At low spray pressures (2 bar and 4 bar), the impact on the droplet diameter of the swirl plates at the 2,0 mm and 2,4 mm nozzle discs reduced. The effect of brown, yellow and stainless steel plates on droplet diameter was found insignificant for the nozzle discs of large orifice diameters.

Table 6 showed the results of the regression analysis between droplet diameter and spray pressure, and the exponential functions for each of the nozzle orifice diameter and swirl plate combinations. Using the exponential functions, the droplet diameter of any orifice diameter and swirl plate combination can be estimated in reference to the spray pressure.

In Table 7, the droplet diameter spray categories were given in the spray pressure range of 2-12 bar in the nozzle disc and swirl plate combinations. Accordingly, the hollow cone nozzles produced mostly thin and medium-sized droplets. Medium-sized droplets produced in nozzle groups with orifice diameter greater than 1,6 mm were obtained at the low spray pressures (2 and 3 bar).

Discussion

The Effect of Swirl Plates on Discharge Rate Variation

It is known that the discharge rates at the hollow cone nozzles alters in reference to the swirl plates. However, there was no any information about the operational characteristics of the and nozzle discs and the swirl plates produced or used locally (Arag®, 2004; Albuz®, 2009; Teejet®, 2014; Hypro®, 2017). Sayıncı et al. (2013) determined that 2-slotted swirl plates varied the flow characteristics and discharge rates of the spray nozzles used together with the 50-mesh size strainer. In the present study, all measurements were performed without using a strainer. As the strainers were known to alter the flow characteristics of the spray nozzles (Sayıncı and Kara, 2015; Sayıncı, 2014; Sayıncı, 2015; Sayıncı, 2016), the nozzle discharge rate and other measurements were performed specific to this study. In conclusion, the swirl plates on the nozzle discs with small orifice diameter have a significant impact, and the effect of the swirl plates on the discharge rate variation gradually decreased as the orifice diameter increased.

Discharge Coefficient

Sayıncı et al. (2013) determined that the discharge coefficients of the hollow cone nozzles with 1,0 mm, 1,2 mm, 1,5 mm, 2,0 mm and 2,5 mm orifice diameters, and the averages was found as 0,402, 0,361, 0,337, 0,232 and 0,184, respectively. Wilkinson et al. (1999) reported that the flow coefficient depends on the orifice geometry of the nozzle and ranged from 0,15 to 0,65. Maniarasan and Nicholas (2006), Chu et al. (2008) and Hussein et al. (2012) stated that the flow coefficient is higher in small orifice nozzles than the larger ones. All literature findings have been consistent with the results of this study. In terms of the nozzle material, Sayıncı et al. (2013) found that the discharge coefficient of polyacetal (POM) nozzle discs was lower than those of ceramic and stainless steel. In terms of the nozzle type, the discharge coefficient ranged between 0.85-0,98 for standard flat fan nozzles (Sayıncı and Kara 2014; Sayıncı, 2015; Zhou et al., 1996; Cloeter et al., 2010; Dorr et al., 2013); 0,67-0,77 for pre-orifice chamber flat fan nozzles (Sayıncı and Kara, 2015); 0,38-0,43 for air-induction flat fan nozzles (Cloeter et al., 2010; Dorr et al., 2013).

Droplet Size

It was determined that the droplet diameter in all nozzle disc and swirl plate combinations in the range of 2-12 bar spray pressure ranged between 76,3-219,0 µm. In this range, the droplets were very fine and fine according to the spray classification indicated in the Hypro® (2014) catalogue, while the droplets were very fine, fine, medium and coarse in reference to Hypropumps® (2006), Kruger et al. (2013), Matthews et al. (2014) and Arag® (2017) literatures. In a study conducted by Serim and Özdemir (2012), droplet diameter measurements were performed at the constant spray pressure of 6 bar for hollow cone nozzles obtained from local manufacturer. The nozzle discs with orifice diameters of 1,0 mm, 1,2 mm and 1,5 mm were separately analysed in five groups and the volumetric median diameters ($D_{V0.50}$) of the four groups were determined in the 115,1-132,7 µm range. In this study, droplet diameters obtained from similar orifice diameter nozzles at 6 bar spray pressure ranged between 97,1-130,4 µm and these results were found compatible with the literature findings.

Conclusion

Spray nozzles, which are one of the most important parts of sprayer equipment, are manufactured from different materials in different types and sizes. The hollow cone nozzles choosing due to their cheap and easy supply are mostly operated at high pressures in the application area and produced very fine droplets sensitive to drift. In this respect, it is of great importance that pesticide applications are carried out under low wind speed conditions. The nozzle discharge coefficient is an important parameter in terms of flow dynamics and nozzle design. In this study, it was determined that the discharge coefficient of hollow cone nozzles was significantly lower than the standard flat fan nozzles. The differences among the discharge coefficients varies considerably depending on the swirl plate used behind the nozzle disc. This result is a reference for new design swirl plates. There is no standardization and quality standardization for the nozzle discs and swirl plates manufactured locally. It is predicted that the nominal size standardization for the hollow cone nozzles will increase the production quality.

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