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Effect of strainer type, spray pressure, and orifice size on the discharge coefficient of standard flat-fan nozzles

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Abstract: The aim of this study was to determine the effect of nozzle strainer type (cylindrical, ball check, slotted, and cup screen type), spray pressure, and nozzle orifice size on the discharge coefficient (C_d) of standard flat-fan nozzles of different nominal sizes (from 02 to 06) and 110° spray angle. The flow rates measured for each nozzle orifice size and strainer type combinations were determined at five different spray pressures (2.0, 3.5, 5.0, 6.5, and 8.0 bars). In the study, size, shape, and area measurements concerned with nozzle geometry were performed and the differences between nozzles of different nominal sizes were revealed. Some of these data were also used to determine the liquid inlet and outlet velocity, discharge coefficient, and minimum spray pressure required for the atomization of nozzles with different strainer types. The liquid inlet and outlet velocity ranged from 4.38 to 11.75 m s^{-1} and 20.49 to 41.72 m s^{-1}, respectively, depending on the spray pressures. The nozzles used with the cup screen and slotted strainers had identical velocity data as the same nozzles without strainers. The cylindrical and ball check strainers had a limiting effect on liquid inlet and outlet velocity, especially for 04 and 06 sizes. The C_d means of the nozzles with cup screen and slotted strainers, and of those without strainers, ranged from 0.874 to 0.980, and the differences between their means were found to be statistically insignificant for each spray pressure and orifice size. The C_d means of the nozzles with cylindrical and ball check strainers were 0.850–0.961 and 0.811–0.963, respectively. The C_d of the standard flat fan nozzles without strainer had a tendency to decrease with the increasing spray pressure, while the C_d means of the nozzles with ball check strainer moderately increased. For the complete atomization, the minimum pressure requirements of the orifices of 02 and 06 size without strainer were 2.03 and 0.99 bars, respectively, corresponding to flow rates of 0.64 and 1.33 L min^{-1}. The required spray pressure for the nozzle with ball check strainer was found to be higher than that of the other strainer types.

Key words: Flow rate, nozzle inlet velocity, nozzle outlet velocity, projected area, pressure exponent

1. Introduction

Flat-fan spray nozzles are widely used nozzle types in pesticide applications. The nozzle orifice, which is rectangular or oval-shaped, is located in the middle of the V-shaped channel on the nozzle body. The spray angles of these nozzles are manufactured with eight different color codes ranging from 65° to 120°. Flow rates of these nozzles are mainly affected by the function of the orifice size and spray pressure, which are the variable parameters. The nozzle flow rate, which is one of the most important measure parameters after manufacturing, is an indicator of nozzle quality. The flow rate at spray pressure of 276 kPa (40 psi) of a nozzle manufactured with different color codes and orifice sizes has been standardized by the ISO International Standards (ISO, 1996) and the American Society of Agricultural and Biological Engineers Standards (ASABE Standards, 2009).

According to hydraulic principles, the flow rate of a nozzle is proportional to the square root of spray pressure. This means that the exponent coefficient of spray pressure is 0.50. This is commonly applied to all nozzles, but it is in fact erroneous to do so. In particular, nonspiral design full cone nozzles and wide angle full cone nozzles have an exponent of 0.46 or 0.44 (Spraying Systems Co., 2014). This information indicates that the flow characteristics of a nozzle depend on its design attributes.

Sayıncı (2014) determined that the nozzle strainers lead to change in the pressure exponent coefficient, which is the relation between flow rates and spray pressures of spray nozzles. The exponent coefficient ranged between 0.48 and 0.49 for the nozzles used with standard types of nozzle strainers, and between 0.55 and 0.57 for the nozzles used with ball check strainers.

Nozzle strainers, which are a crucial part of a sprayer, are located in the nozzle body to screen out the debris

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clogging the nozzle orifice. The type of nozzle strainer needed depends on the size of the nozzle opening and the type of sprayed chemical (Waxman, 1998). The strainer numbers state the number of openings per length of 25.4 mm. The strainers with high mesh numbers have smaller openings than strainers with low mesh numbers (Hofman and Solseng, 2004).

There are many types of nozzle strainers, the mesh sizes of which range between 24 and 200 meshes (Agrotop, 2010). Most of them are manufactured from brass, aluminum, polypropylene, and stainless steel materials. Cylindrical, slotted, and cup strainers are the most widely used types, and are located behind the spray nozzle in the body. The nozzle strainers with a check valve are a good way to prevent clogging and to decrease nozzle dripping when the boom control valve is closed. These strainers may provide the possibility of obtaining equal pressure before spraying.

It is clear that nozzle strainers have a limiting effect on the flow at the outlet orifice of the spray liquid (Sayıncı, 2014). This limitation of the spray nozzles can result from the discharge coefficient, and varies for different types of strainers. The discharge coefficient is the ratio of the mass of volumetric flow rate at the discharge outlet orifice of the nozzle to that of an ideal nozzle, which expands an identical working fluid under the same initial conditions at the same spray pressure. In other words, this coefficient provides information about the constrictions of the nozzle.

There are a few studies concerning the discharge coefficient of agricultural spray nozzles. Research concerned with the flow characteristics of the spray nozzles within the fluid mechanics is indispensable for new nozzle designs. The aim of this study was to determine the discharge coefficient of standard flat-fan nozzles with different types of strainers, to reveal the liquid inlet and outlet velocity for the nozzle orifice size and strainer type combinations, and to calculate the minimum spray jet velocity and required spray pressure for atomization.

2. Materials and methods

2.1. Spray nozzles

Four flat-fan nozzles of different orifice sizes (02, 03, 04, and 06) were used for this study. The nominal size of the nozzles and nozzle body color met the American Society of Agricultural and Biological Engineers' standards (ASABE Standards, 2009). The nozzles' orifice dimensions and shapes are given in Table 1. All dimensions (length, width, and nozzle input section diameter) of the nozzle orifice in Figure 1 were measured using a stereo zoom microscope (Olympus SZ60, JP) equipped with a micrometer and digital camera (Panasonic Lumix DMC-FZ50, JP). Orifice's projected area (PA_m) was determined with an image processing method using SigmaScan Pro software.

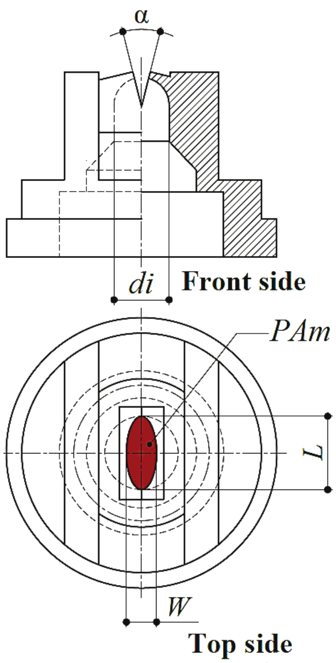


Figure 1. Indications concerned with orifice dimensions (L and W), V-cut angle (α), and projected area (PA_m) of a standard flat-fan nozzle.

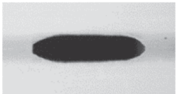
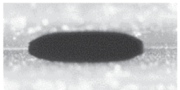
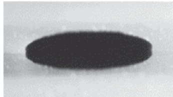
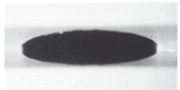
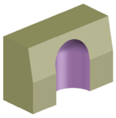
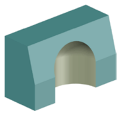
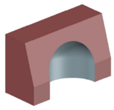
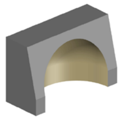
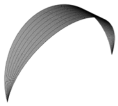
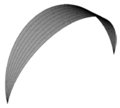
In order to determine the orifice opening area (A_o), 3D solid modelling of a flat-fan nozzle with reference to the orifice dimensions was generated using AutoCAD software (version 2015). After the 3D surfaces of orifice opening in V-slot were copied, a mesh surface was created between two reciprocal surfaces, the edge of which was curved, as seen in Table 1. The meshed orifice opening was converted to surface using the mesh modelling interface, and its opening area was determined using the area command.

To calculate the projected area (PA_c) of the nozzle orifice with different nominal sizes based on the nozzle's nominal flow rate at constant spraying pressure, Eq. (1), derived from the Bernoulli equation, was used.

$$PA_c = \frac{Q_n}{\sqrt{\frac{2 \cdot \Delta P_c}{\rho_L}}} \cdot 10^6 \qquad (1)$$

The equivalent orifice diameter (d_{eq}) was calculated using the basic area equation $\left(d_{eq} = 2 \cdot \sqrt{PA_m/\pi}\right)$ based on its measured projected area (PA_m). Zhou et al. (1996) reported that the spray angle (θ) depended on the V-cut angle (α) of the nozzle. The relation between both parameters presented with a polynomial equation can be seen in Eq. (2).

Table 1. Dimensions, areas, and shape properties of standard flat-fan nozzle orifices.

Properties	Nozzle nominal size			
	02	03	04	06
Projected image of orifice				
3D modeling (longitudinal section)				
3D orifice opening				
Orifice shape	Oval	Oval	Oval	Oval
[1]Projected area (PA_m, mm^2)	0.52	0.82	1.06	1.68
[2]Eq. orifice diam. (d_{eq}, mm)	0.81	1.02	1.16	1.46
[3]Inlet diameter (d_i, mm)	1.55	1.85	2.15	2.85
[4]Length (L, mm)	1.54	1.84	2.1	2.83
[5]Width (W, mm)	0.38	0.52	0.64	0.73
[6]Projected area (PA_c, mm^2)	0.54	0.81	1.08	1.62
[7]Orifice area (A_o, mm^2)	0.65	0.99	1.41	2.12
V-cut angle (θ°)	23	30	32	28
Nominal spray angle (α_n°)	110	110	110	110
Calculated spray angle (α_c°)	120	104	100	108

[1]: measurement; [2]: equivalent orifice diameter calculated from the measured projected area; [3]: nozzle orifice inlet diameter; [4]: major orifice size; [5]: minor orifice size; [6]: calculation; [7]: orifice area calculated from the orifice opening generated after 3D surface modeling.

$$\theta = 188.67 - 7.27\left(\frac{\alpha}{2}\right) + 1.19 \cdot 10^{-1}\left(\frac{\alpha^2}{2}\right) - 7.99 \cdot 10^{-4}\left(\frac{\alpha^3}{2}\right) \quad (2)$$

2.2. Strainer types

In this study, three cylindrical strainers of 40, 50, and 80 meshes, two ball check strainers of 50 and 80 meshes, a slotted strainer of 50 meshes made of brass, and a screen cup strainer of 50 meshes were used. Their screen types and technical dimensions are given in Table 2.

The strainer types used in this study were evaluated under three groups and compared to the usage without strainer in terms of the parameters concerned with the discharge. The cup screen type strainer and slotted strainer formed group 1, the cylindrical strainers formed group 2, and the ball check strainers formed group 3.

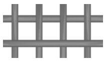
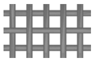
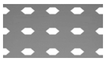
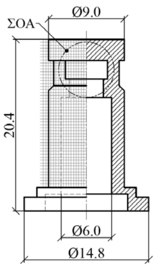
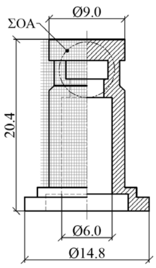
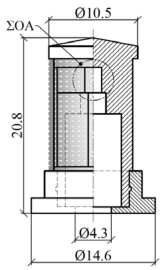
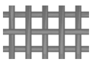
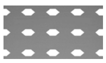
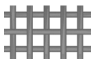
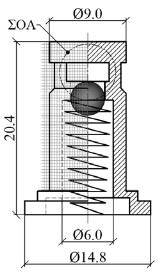
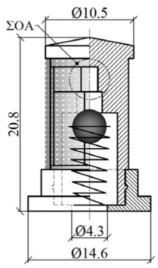
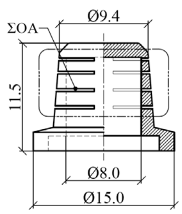
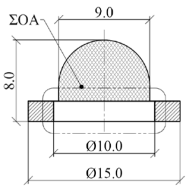
2.3. Sprayer and power unit

In the study, a conventional sprayer (TP 200 Piton, Turkey) with a 200-L polyethylene tank was used to determine the flow rate of the nozzles. A spray frame with adjustable height was manufactured instead of the standard boom length of 6.0 m. Spraying pressure was adjusted using a pressure regulator on the spray line. Spray pressure of the nozzle combinations was controlled using a digital manometer (Ref D2, 0.1%, 0–400 bars, SİKA GmbH & Co. KG), which was mounted on the nozzle body. Two diaphragm-positive displacement pumps (Tar30 type, Taral, Turkey) of 30 L min^{-1} flow rate and 39.2 bars pressure were used on the sprayer. An electric motor of 2.2 kW was used as power supply to drive the pump shaft (AGM 100L 4a type, Gamak, Turkey) of the sprayer. The pump shaft revolution was constant at 500 min^{-1}. The shaft revolution was decreased at a rate of 1:2.8 using a belt and pulley mechanism.

2.4. Nozzle flow rate

The flow rates of the nozzles were determined at five different spray pressures (2.0, 3.5, 5.0, 6.5, and 8.0 bars). Spray pressure was adjusted with a pressure regulator, and the pressures were measured using a digital manometer (Ref D2, 0.1%, 0–400 bars, SİKA GmbH & Co. KG). An adaptor equipped with a manometer was mounted instead

Table 2. Technical properties of the nozzle strainer types.

Properties	Cylindrical strainers			
Strainer images				
Mesh size	40 mesh	50 mesh	80 mesh	
Screen material	Cr-Ni	Cr-Ni	Stainless steel	
Type	Screen	Screen	Perforated sheet	
Screen shape	Square	Square	Hexagon	
Screen pattern				
Screen size (mm)	0.5 × 0.5	0.3 × 0.3	0.2 × 0.4**	
Strainer dimensions				
Properties	Ball-check strainers		Slotted strainer	Cup screen type strainer
Strainer images				
Mesh size	50 mesh	80 mesh	50 mesh	50 mesh
Screen material	Cr-Ni	Stainless steel	Brass	Cr-Ni
Type	Screen	Perforated sheet	Slotted	Screen
Screen shape	Square	Hexagon	Slot	Square
Screen pattern				
Strainer dimensions				

**: minor and major lengths of opening shaped hexagon (mm) of the nozzle cap and this allowed the precise readings of the spray pressure at the location of the nozzle holder. The flow rates of the nozzles were measured with regard to the mass principle. A quantity of liquid collected in a measuring glass after 60 s was weighed using an electronic balance with precision of a milligram (0.001 g). The tare weight of the measuring glass was removed from each of the measurements. To calculate the volumetric flow rate from the mass flow rate, liquid density of 17.5 °C was measured using a digital probe thermometer. The flow rate measurements were replicated three times for each combination of nozzle size, strainer type, and spray pressure.

2.5. Liquid inlet velocity

The nozzle inlet section diameter (d_i), shown in Figure 1, increased with the increasing orifice size of the nozzles, as seen in Table 1. The different d_i values caused changes in liquid velocity (U_i) at the nozzle inlet for different spray pressures. The liquid inlet velocity was calculated with Eq. (3) based on the Bernoulli equation (Zhou et al., 1996):

$$U_i = \frac{4 \cdot Q_a}{\pi \cdot d_i^2} \tag{3}$$

2.6. Liquid outlet velocity

According to the equation reported by Zhou et al. (1996), the liquid outlet velocity (U_e) without head loss can be calculated using Eq. (4) based on the function of the inlet liquid velocity and spray pressure measured from the back of the nozzle cap.

$$U_e = \sqrt{U_i^2 + \frac{2 \cdot \Delta P}{\rho_L}} \tag{4}$$

2.7. Discharge coefficient

Discharge coefficient represents the ratio of the actual liquid flow rate to that theoretically possible, and the volumetric flow rate can be calculated with Eq. (5) (Srivastava et al., 1993; Yu et al., 2013).

$$Q_a = C_d \cdot Q_i = C_d \cdot PA_m \cdot U_e = C_d \cdot PA_m \cdot \sqrt{U_i^2 + \frac{2 \cdot \Delta P}{\rho_L}} \tag{5}$$

The discharge coefficient (C_d) in Eq. (6) can be written from Eq. (5) as:

$$C_d = \frac{Q_a}{Q_i} = \frac{Q_a}{PA_m \cdot \sqrt{U_i^2 + \frac{2 \cdot \Delta P}{\rho_L}}} \tag{6}$$

2.8. Maximum droplet velocity

The maximum droplet velocity (V_{max}, m s^{-1}) close to the nozzle outlet was calculated based on the nozzle's C_d using Eq. (7,) referring to Bernoulli's equation (Al Heidary et al., 2014).

$$V_{max} = C_d \cdot U_e \tag{7}$$

2.9. Minimum nozzle flow rate required to produce atomization

The minimum jet velocity required to produce atomization, which depends on the physical properties of the spray liquid, was calculated using Eq. (8) (Srivastava et al., 1993).

$$V_j > 280 \cdot \frac{\sigma^{0.41}}{\rho_L^{0.59}} \cdot \frac{\mu^{0.18}}{d_i^{0.59}}, \tag{8}$$

where d_i is the nozzle inlet section diameter in mm.

To calculate the minimum nozzle flow rate ($Q_{min,}$ m^3 s^{-1}) corresponding to the minimum jet velocity (V_j, m s^{-1}), Eq. (9) was used (Srivastava et al., 1993). This is the minimum nozzle flow rate value that is required for the atomization.

$$Q_{min} = V_j \cdot C_d \cdot PA_m \tag{9}$$

2.10. Minimum spray pressure to produce atomization

The relation between volumetric flow rate (Q_a) and spray pressure (ΔP) for the standard flat-fan nozzles was determined using the power regression model for each combination of the nominal sizes and strainer types (Sayıncı, 2014). The *k* coefficient, referred to as the orifice coefficient in the ASABE standards (2009), elucidates the relation between nozzle flow rate and spray pressure. The pressure exponent (n) is generally accepted as 0.50 due to its inherent simplicity and near universality (Tanner and Knasiak, 2007). However, Sayıncı (2014) experimentally determined the pressure exponents (n) for the standard type flat-fan nozzles with different strainer types, and the n coefficients were found to be different than 0.50, which is accepted theoretically. The k and n coefficients used in the study are given in Table 3. Using the power regression model, the minimum spray pressure (P_{min}) required to produce atomization was calculated with Eq. (10).

$$P_{min} = \left(\frac{Q_{min}}{k}\right)^{1/n} \tag{10}$$

2.11. Statistical analysis

The effect of the nozzle orifice size and strainer type on liquid velocity and discharge coefficient was tested using the analysis of variance (ANOVA) procedure. The minimum flow rate means, corresponding to the liquid

Table 3. The orifice coefficient (*k*) and pressure exponent (*n*) means of the power regression model explaining the relation between flow rate and pressure for the standard flat-fan nozzles used with different strainer types (the means were determined experimentally by Sayıncı (2014)).

Strainer types	Nozzle nominal size 02			03			04			06		
	k	*n*	R^2	*k*	*n*	R^2	*k*	*n*	R^2	*k*	*n*	R^2
No strainer	0.457	0.476	0.998	0.679	0.481	0.993	0.929	0.487	0.994	1.321	0.483	0.994
Cup screen - 50 mesh	0.444	0.491	0.998	0.682	0.476	0.995	0.919	0.493	0.992	1.335	0.482	0.996
Slotted str. - 50 mesh	0.450	0.487	0.998	0.666	0.494	0.995	0.916	0.487	0.991	1.329	0.481	0.994
Cylindrical - 40 mesh	0.447	0.487	0.998	0.657	0.497	0.994	0.915	0.488	0.993	1.297	0.482	0.995
Cylindrical - 50 mesh	0.443	0.492	0.998	0.666	0.489	0.995	0.896	0.491	0.993	1.308	0.480	0.993
Cylindrical - 80 mesh	0.439	0.495	0.999	0.674	0.478	0.994	0.902	0.494	0.993	1.278	0.482	0.994
Ball check - 50 mesh	0.368	0.585	0.992	0.601	0.527	0.993	0.829	0.514	0.994	1.145	0.518	0.993
Ball check - 80 mesh	0.330	0.641	0.991	0.531	0.607	0.981	0.805	0.537	0.996	1.222	0.487	0.997

jet velocity obtained from the minimum flow rates, were tabulated. A completely randomized design and SPSS was used for the ANOVA with a 95% confidence level (P = 0.05), and Duncan's multiple comparison test was used to determine significant differences.

3. Results

3.1. Evaluation of the nozzle geometry

The shape of all nozzle orifices was elliptical. The V-cut angle caused the width size of the orifice, the shape of which is ellipse, to vary. The projected area (PA_m) data obtained by measurement in Table 1 were found to be considerably close to the data of PA_c. Despite the slight differences between the nozzle inlet diameter and the orifice's major length, both data were considered equivalent.

3.2. Liquid inlet and outlet velocity

The results of ANOVA showed that the nozzle orifice size and strainer type for different spray pressures had a significant effect on the liquid inlet and outlet velocity (P < 0.01). The liquid inlet velocity in Table 4 varied from 4.38 to 11.75 m s^{-1} depending on the spray pressures. The liquid outlet velocity was found to be higher than the inlet velocity, and the means ranged from 20.49 to 41.72 m s^{-1}. As the spray pressure increased, the liquid inlet and outlet velocities also increased. Due to head loss, the maximum droplet velocity data in Table 5 were lower than the liquid outlet velocity, and the means varied from 16.62 to 40.01 m s^{-1}.

In general, regarding the velocity data, the nozzles used with the cup screen and slotted strainers had identical velocities that were equivalent to those of the nozzles without strainers. The lowest velocity data were obtained with the ball check strainers. It was clearly shown that there were no differences between the velocity data of the 02 and 03 nozzles used with the cup screen, slotted and cylindrical strainer types, and without a strainer. For the 04 and 06 nozzles, the cylindrical and ball check strainer types had a limiting effect on the liquid inlet and outlet velocity. However, the liquid velocity data of the 02 nozzle, with the ball check strainer at spray pressure of 8 bars, were found higher than the other strainer types.

3.3. Factors affecting the discharge coefficient (C_d)

According to the results of ANOVA, the effect of the strainer type, spray pressure, and orifice size on the discharge coefficient (C_d) of the standard flat-fan nozzle was found to be statistically very significant (P < 0.01). In general, the Duncan's test results given in Table 6 indicated that the C_d means of the nozzles without strainers were similar to those of the cup screen and slotted strainers. The C_d means of the cylindrical strainers were lower than that without a strainer. Among the strainer types, the ball check strainers had the lowest C_d means for all spray pressures and orifice sizes, except for the nozzle of 02 orifice size at spray pressure of 8 bars.

In general, the differences between the C_d means of the nozzles with cup screen and slotted strainers and those without strainers were statistically insignificant, ranging from 0.874 to 0.980. The C_d means of the nozzles used with the cylindrical and ball check strainers were 0.850–0.961 and, 0.811–0.963, respectively (Table 6).

Table 4. Liquid velocity (m s^{-1}) at the nozzle orifice inlet and outlet.

Liquid velocity (m s^{-1})	Pressure (bar)	Strainer types	Nozzle nominal size			
			02	03	04	06
Inlet velocity	2.0	No strainer	5.61 ± 0.07a*	5.88 ± 0.14a	5.98 ± 0.13a	4.82 ± 0.12a
		Cup and slotted	5.55 ± 0.07ab	5.85 ± 0.11a	5.92 ± 0.17ab	4.86 ± 0.08a
		Cylindrical	5.50 ± 0.05b	5.79 ± 0.12a	5.83 ± 0.16b	4.72 ± 0.10b
		Ball check	4.72 ± 0.18c	5.19 ± 0.23b	5.40 ± 0.11c	4.38 ± 0.13c
	3.5	No strainer	7.33 ± 0.07a	7.69 ± 0.18a	7.86 ± 0.16a	6.38 ± 0.14a
		Cup and slotted	7.29 ± 0.07a	7.67 ± 0.14a	7.78 ± 0.19ab	6.36 ± 0.12a
		Cylindrical	7.24 ± 0.07a	7.61 ± 0.15a	7.68 ± 0.18b	6.18 ± 0.12b
		Ball check	6.65 ± 0.14b	7.13 ± 0.17b	7.25 ± 0.14c	5.80 ± 0.12c
	5.0	No strainer	8.68 ± 0.08a	9.13 ± 0.21a	9.34 ± 0.18a	7.58 ± 0.17a
		Cup and slotted	8.68 ± 0.08a	9.12 ± 0.18a	9.27 ± 0.20ab	7.56 ± 0.15a
		Cylindrical	8.63 ± 0.08a	9.06 ± 0.18a	9.15 ± 0.19b	7.34 ± 0.15b
		Ball check	8.27 ± 0.10b	8.73 ± 0.17b	8.74 ± 0.17c	6.94 ± 0.13c
	6.5	No strainer	9.84 ± 0.08a	10.36 ± 0.24a	10.62 ± 0.19a	8.60 ± 0.20a
		Cup and slotted	9.87 ± 0.09a	10.36 ± 0.22a	10.54 ± 0.21ab	8.57 ± 0.18a
		Cylindrical	9.82 ± 0.10a	10.29 ± 0.22a	10.40 ± 0.19b	8.33 ± 0.17b
		Ball check	9.71 ± 0.09b	10.12 ± 0.23a	10.04 ± 0.21c	7.92 ± 0.16c
	8.0	No strainer	10.86 ± 0.09b	11.45 ± 0.26a	11.75 ± 0.21a	9.51 ± 0.22a
		Cup and slotted	10.92 ± 0.10b	11.45 ± 0.26a	11.67 ± 0.22ab	9.48 ± 0.21a
		Cylindrical	10.87 ± 0.11b	11.39 ± 0.26a	11.52 ± 0.20b	9.20 ± 0.19b
		Ball check	11.03 ± 0.12a	11.39 ± 0.33a	11.20 ± 0.25c	8.79 ± 0.20c
Outlet velocity	2.0	No strainer	20.79 ± 0.02a	20.86 ± 0.04a	20.89 ± 0.04a	20.59 ± 0.03a
		Cup and slotted	20.77 ± 0.02ab	20.86 ± 0.03a	20.87 ± 0.05ab	20.60 ± 0.02a
		Cylindrical	20.76 ± 0.01b	20.84 ± 0.03a	20.85 ± 0.05b	20.57 ± 0.02a
		Ball check	20.57 ± 0.04c	20.68 ± 0.06b	20.73 ± 0.03c	20.49 ± 0.03b
	3.5	No strainer	27.48 ± 0.02a	27.58 ± 0.05a	27.62 ± 0.04a	27.24 ± 0.03a
		Cup and slotted	27.47 ± 0.02ab	27.57 ± 0.04a	27.60 ± 0.05ab	27.24 ± 0.03a
		Cylindrical	27.45 ± 0.02b	27.55 ± 0.04a	27.57 ± 0.05b	27.19 ± 0.03b
		Ball check	27.30 ± 0.03c	27.42 ± 0.04b	27.46 ± 0.04c	27.11 ± 0.02c
	5.0	No strainer	32.82 ± 0.02a	32.94 ± 0.06a	33.00 ± 0.05a	32.55 ± 0.04a
		Cup and slotted	32.82 ± 0.02a	32.94 ± 0.05a	32.98 ± 0.06ab	32.54 ± 0.04a
		Cylindrical	32.81 ± 0.02a	32.92 ± 0.05a	32.95 ± 0.05b	32.49 ± 0.03b
		Ball check	32.71 ± 0.03b	32.83 ± 0.04b	32.84 ± 0.04c	32.40 ± 0.03c
	6.5	No strainer	37.40 ± 0.02a	37.55 ± 0.07a	37.62 ± 0.06a	37.1 ± 0.040a
		Cup and slotted	37.41 ± 0.02a	37.55 ± 0.06a	37.60 ± 0.06ab	37.09 ± 0.04a
		Cylindrical	37.40 ± 0.03a	37.53 ± 0.06a	37.56 ± 0.05b	37.04 ± 0.04b
		Ball check	37.37 ± 0.02b	37.48 ± 0.06a	37.46 ± 0.06c	36.95 ± 0.03c
	8.0	No strainer	41.48 ± 0.02b	41.64 ± 0.07a	41.72 ± 0.06a	41.15 ± 0.05a
		Cup and slotted	41.50 ± 0.03b	41.64 ± 0.07a	41.70 ± 0.06ab	41.14 ± 0.05a
		Cylindrical	41.49 ± 0.03b	41.63 ± 0.07a	41.66 ± 0.06b	41.08 ± 0.04b
		Ball check	41.53 ± 0.03a	41.63 ± 0.09a	41.57 ± 0.07c	40.99 ± 0.04c

*: Means followed by the same letter in the same column are not different as determined by the Duncan's test at a 5% significance level.

Table 5. Maximum droplet velocity (m s^{-1}) at the nozzle orifice outlet.

Pressure (bar)	Strainer types	Nozzle nominal size			
		02	03	04	06
2.0	No strainer	20.36 ± 0.24a*	19.25 ± 0.46a	20.48 ± 0.44a	18.31 ± 0.44a
	Cup and slotted	20.11 ± 0.26ab	19.16 ± 0.36a	20.26 ± 0.58ab	18.45 ± 0.31a
	Cylindrical	19.95 ± 0.20b	18.97 ± 0.39a	19.97 ± 0.55b	17.93 ± 0.37b
	Ball check	17.11 ± 0.64c	17.02 ± 0.75b	18.49 ± 0.38c	16.62 ± 0.48c
3.5	No strainer	26.57 ± 0.27a	25.20 ± 0.59a	26.89 ± 0.54a	24.22 ± 0.53a
	Cup and slotted	26.43 ± 0.27a	25.14 ± 0.46a	26.64 ± 0.63ab	24.15 ± 0.45a
	Cylindrical	26.27 ± 0.24a	24.93 ± 0.49a	26.28 ± 0.61b	23.47 ± 0.47b
	Ball check	24.10 ± 0.51b	23.35 ± 0.56b	24.81 ± 0.46c	22.02 ± 0.44c
5.0	No strainer	31.49 ± 0.29a	29.92 ± 0.69a	31.99 ± 0.61a	28.77 ± 0.64a
	Cup and slotted	31.47 ± 0.29a	29.88 ± 0.58a	31.73 ± 0.68ab	28.67 ± 0.58a
	Cylindrical	31.30 ± 0.30a	29.67 ± 0.60a	31.31 ± 0.64b	27.86 ± 0.56b
	Ball check	29.99 ± 0.36b	28.58 ± 0.55b	29.93 ± 0.58c	26.34 ± 0.48c
6.5	No strainer	35.68 ± 0.31a	33.95 ± 0.78a	36.34 ± 0.67a	32.65 ± 0.74a
	Cup and slotted	35.78 ± 0.32a	33.93 ± 0.71a	36.09 ± 0.71ab	32.53 ± 0.70a
	Cylindrical	35.60 ± 0.36a	33.72 ± 0.72a	35.61 ± 0.67b	31.61 ± 0.65b
	Ball check	35.23 ± 0.31b	33.17 ± 0.76a	34.36 ± 0.72c	30.05 ± 0.60c
8.0	No strainer	39.38 ± 0.32b	37.52 ± 0.86a	40.21 ± 0.73a	36.09 ± 0.83a
	Cup and slotted	39.60 ± 0.35b	37.53 ± 0.84a	39.95 ± 0.76ab	35.95 ± 0.81a
	Cylindrical	39.43 ± 0.42b	37.32 ± 0.84a	39.43 ± 0.69b	34.93 ± 0.74b
	Ball check	40.01 ± 0.43a	37.32 ± 1.09a	38.32 ± 0.86c	33.36 ± 0.75c

*: Means followed by the same letter in the same column are not different as determined by the Duncan's test at a 5% significance level.

3.4. Nozzle flow rate and spray pressure corresponding to minimum spray jet velocity

Table 7 showed the nozzle flow rate and spray pressure corresponding to the minimum spray jet velocity depending on the physical features of the spray liquid. These minimal requirements were necessary for the formation of the complete atomization. The flow rate averages of 0.64 and 0.86 L min^{-1} for the nozzles of 02 and 03 sizes, respectively, were required to realize the atomization, and the differences between the means of cup screen, slotted, and usage without strainer for 02 and 03 nozzle orifice sizes were insignificant. The lowest flow rate requirement was obtained with the ball check strainer, and the means ranged from 0.60 to 1.22 L min^{-1} for the orifice size interval from 02 to 06. Spray pressure requirement of the ball check strainer was higher than in other strainer types. As the orifice size increased from 02 to 06, the spray pressure requirements of the nozzles with cup screen, slotted, cylindrical strainers, and without strainers were statistically insignificant. To realize the atomization, the minimum spray pressure requirement was higher than 2.0 bars for the 02 size nozzle orifices. For the orifice of 06 nozzles, the spray pressure of 0.99 bars was found to be enough for the complete atomization.

4. Discussion

The data in Table 1 were concerned with the nozzle geometry and were important in terms of the nozzle design parameters. The projected area of the nozzle had a varying effect on its discharge rate according to the Bernoulli equation. The projected areas (PA_c) of the nozzle orifices shown in Table 1 were calculated with reference to their orifice sizes, and these sizes were the values required to obtain the nozzle's nominal flow rate. The measured

Table 6. The effect of the strainer types on discharge coefficient corresponding to the different spray pressures for each of the nozzle orifice sizes.

Pressure (bar)	Strainer types	Nozzle nominal size			
		02	03	04	06
2.0	No strainer	0.979 ± 0.011a*	0.923 ± 0.020a	0.980 ± 0.020a	0.889 ± 0.020a
	Cup and slotted	0.968 ± 0.012ab	0.919 ± 0.016a	0.970 ± 0.026ab	0.896 ± 0.014a
	Cylindrical	0.961 ± 0.009b	0.910 ± 0.017a	0.958 ± 0.024b	0.872 ± 0.017b
	Ball check	0.832 ± 0.030c	0.823 ± 0.034b	0.892 ± 0.017c	0.811 ± 0.022c
3.5	No strainer	0.967 ± 0.009a	0.914 ± 0.019a	0.973 ± 0.018a	0.889 ± 0.019a
	Cup and slotted	0.963 ± 0.009a	0.912 ± 0.015a	0.965 ± 0.021ab	0.887 ± 0.016a
	Cylindrical	0.957 ± 0.008a	0.905 ± 0.016a	0.953 ± 0.020b	0.863 ± 0.016b
	Ball check	0.883 ± 0.018b	0.851 ± 0.019b	0.904 ± 0.016c	0.812 ± 0.016c
5.0	No strainer	0.959 ± 0.008a	0.908 ± 0.019a	0.969 ± 0.017a	0.884 ± 0.019a
	Cup and slotted	0.959 ± 0.008a	0.907 ± 0.016a	0.962 ± 0.019ab	0.881 ± 0.017a
	Cylindrical	0.954 ± 0.009a	0.901 ± 0.017a	0.950 ± 0.018b	0.857 ± 0.016b
	Ball check	0.917 ± 0.010b	0.871 ± 0.015b	0.911 ± 0.016c	0.813 ± 0.014c
6.5	No strainer	0.954 ± 0.008a	0.904 ± 0.019a	0.966 ± 0.017a	0.880 ± 0.019a
	Cup and slotted	0.956 ± 0.008a	0.904 ± 0.017a	0.960 ± 0.018ab	0.877 ± 0.018a
	Cylindrical	0.952 ± 0.009a	0.898 ± 0.018a	0.948 ± 0.016b	0.853 ± 0.017b
	Ball check	0.943 ± 0.008b	0.885 ± 0.019a	0.917 ± 0.018c	0.813 ± 0.015c
8.0	No strainer	0.949 ± 0.007b	0.901 ± 0.019a	0.964 ± 0.016a	0.877 ± 0.019a
	Cup and slotted	0.954 ± 0.008b	0.901 ± 0.018a	0.958 ± 0.017ab	0.874 ± 0.018a
	Cylindrical	0.950 ± 0.009b	0.896 ± 0.019a	0.946 ± 0.015b	0.850 ± 0.017b
	Ball check	0.963 ± 0.010a	0.897 ± 0.024a	0.922 ± 0.019c	0.814 ± 0.017c

*: Means followed by the same letter in the same column are not different, as determined by the Duncan's test at a 5% significance level.

projected area (PA_m) data were found considerably close to the data of PA_c, in spite of the low optical resolution and minimal depth (Ozkan, 1992) of the stereo zoom microscopy. Despite the minimal differences between the nozzle inlet diameter and orifice's major length, both dimensions were considered to be equivalent. The V-cut angle of the nozzle tended to increase with orifice size, although the 04 nozzle provided the highest angle value. The spray angle values estimated for each nozzle orifice were found close to the nominal spray angle of the nozzles. The slight differences in size originated from the measurement errors and caused the nozzle discharge and liquid velocity to vary. However, the referenced data corrected the measurements.

In general, the ball check strainers caused the nozzles to decrease the liquid velocity compared to other strainer types. The ball check strainers have a spring and a ball preventing any pesticide from dropping from the nozzle's outlet orifice. The spring in a strainer's body takes on a restrictor task, which is indispensable for nozzle holders without membrane. However, the ball check strainers used with the 02 nozzle at a high spray pressure of 8 bars increased the liquid velocity. This stance showed that the ball check strainers used with the nozzles of smaller capacity at high spray pressures had no restrictor effect on liquid velocity. It is clear that increasing the spray pressure for the nozzles induced the production of a finer spray and increased the velocity of droplets leaving the region spray formation (Farooq et al., 2001).

The discharge coefficient (C_d) is equal to the multiple of the area coefficient (C_a) and the velocity coefficient (C_v). It has been stated that C_v varies from 0.95 to 0.99 for a jet

Table 7. Minimum nozzle flow rate (L min^{-1}) and required spray pressure (bar) for atomization.

Properties	Strainer types	Nozzle nominal size			
		02	03	04	06
Min. flow rate, L min^{-1}	No strainer	0.64 ± 0.01a*	0.86 ± 0.02a	1.08 ± 0.02a	1.33 ± 0.03a
	Cup and slotted	0.64 ± 0.01a	0.86 ± 0.02a	1.08 ± 0.02a	1.32 ± 0.03a
	Cylindrical	0.64 ± 0.01a	0.85 ± 0.02a	1.06 ± 0.02b	1.29 ± 0.03b
	Ball check	0.60 ± 0.03b	0.82 ± 0.03b	1.02 ± 0.02c	1.22 ± 0.03c
Minimum spray pressure, bar	No strainer	2.03 ± 0.05c	1.64 ± 0.03b	1.37 ± 0.02b	0.99 ± 0.03b
	Cup and slotted	2.07 ± 0.04bc	1.65 ± 0.05b	1.39 ± 0.05b	0.99 ± 0.03b
	Cylindrical	2.08 ± 0.03b	1.66 ± 0.05b	1.39 ± 0.04b	0.99 ± 0.04b
	Ball check	2.45 ± 0.22a	1.92 ± 0.18a	1.52 ± 0.06a	1.06 ± 0.08a

*: Means followed by the same letter in the same column are not different, as determined by the Duncan's test at a 5% significance level.

leaving the square-edged or rounded orifice. For ideal flow conditions, C_a has been reported as 0.61 (Streeter, 1966; Leinhard, 1984; Srivastava et al., 1993). In that case, C_v and C_a can be acceptable values for the disc-core type cone nozzles due to its rounded orifice. Wilkinson et al. (1999) stated that C_d for spray nozzles ranged from 0.15 to 0.65 for spray nozzles. C_d values for the hollow cone nozzle were determined between 0.35 and 0.73 (Iqbal et al., 2005). These ranges are considerably wide for the spray nozzles. Particularly, Rashid et al. (2012) have emphasized that the C_d of the solid cone nozzles is constant at 0.60. Sayıncı et al. (2013) determined that the C_d for disc-core type hollow cone nozzles varied with regard to their manufacturing material. In their study, C_d was 0.141–0.457 for disc-core type hollow cone nozzles made of POM material, 0.453–0.560 for the nozzles made of stainless steel, and 0.439–0.608 for the nozzles made of ceramic.

In general, the flat-fan nozzles had a higher C_d value than disc-core type cone nozzles. It was stated that the C_d values of a new concept variable flow-fan nozzle developed by Womac and Bui (2002) were 0.647–0.959. Zhou et al. (1996) determined that the C_d of the flat fan nozzles varied between 0.91 and 0.98. The C_d values obtained from this study were found compatible with the literature findings.

Hussein et al. (2012) reported that the C_d value for the hollow cone and solid cone nozzles decreased with increasing orifice size. Similar findings were also confirmed in the study conducted by Sayıncı et al. (2013) and in the present study. It might be concluded that this trend attained for the hollow cone nozzles was also valid for the standard flat-fan nozzles, because the C_d means of the flat fan nozzles used with the cup screen, slotted, cylindrical, and without strainer had a tendency to decrease with the increasing spray pressure, as seen in Figure 2. For instance, the C_d means of the nozzle of 02 size without a strainer decreased from 0.979 to 0.949 at the spray pressure intervals ranging from 2.0 to 8.0 bars. Conversely, the C_d means of the nozzles with the ball check strainer increased fairly with the increasing spray pressure, ranging from 2.0 to 8.0 bars. However, this increasing rate for the nozzle of 06 size, the C_d means of which ranged from 0.811 to 0.814 at the spray pressure intervals ranging from 2.0 to 8.0 bars (Table 6), remained at the minimal level compared to the orifice sizes of 02, 03, and 04. This situation showed that the C_d means of the nozzles used with the ball check strainer tended to remain constant as the nozzle orifice size increased (Figure 2).

Furthermore, it was noted that the cylindrical strainer caused the C_d means of the nozzle orifices of 04 and 06 sizes to decrease explicitly. This distinction for the cylindrical strainer tended to increase with the increasing orifice size from 02 to 06 (Figure 2). This attribute of the cylindrical strainers might be considered as an important factor limiting the flow of the nozzles, which is higher than 04 orifice size.

By increasing the nozzle's orifice size, the differences among the strainer types in terms of minimal flow rate and spray pressure were revealed, as seen in Table 7. The flow rate requirement for the cup screen, slotted, and without strainer was explicitly found different than those of the cylindrical and ball check strainers. Ball check strainer is manufactured to prevent dripping after spraying. These types of strainers are mostly used with nozzle holders with no membrane. In general, when operational pressure drops to 1.0 bar, the ball in the strainer body closes the fluid line to prevent dripping. Some manufacturers have indicated that this operational pressure drop for the ball check strainers decreased up to 0.34 bars.

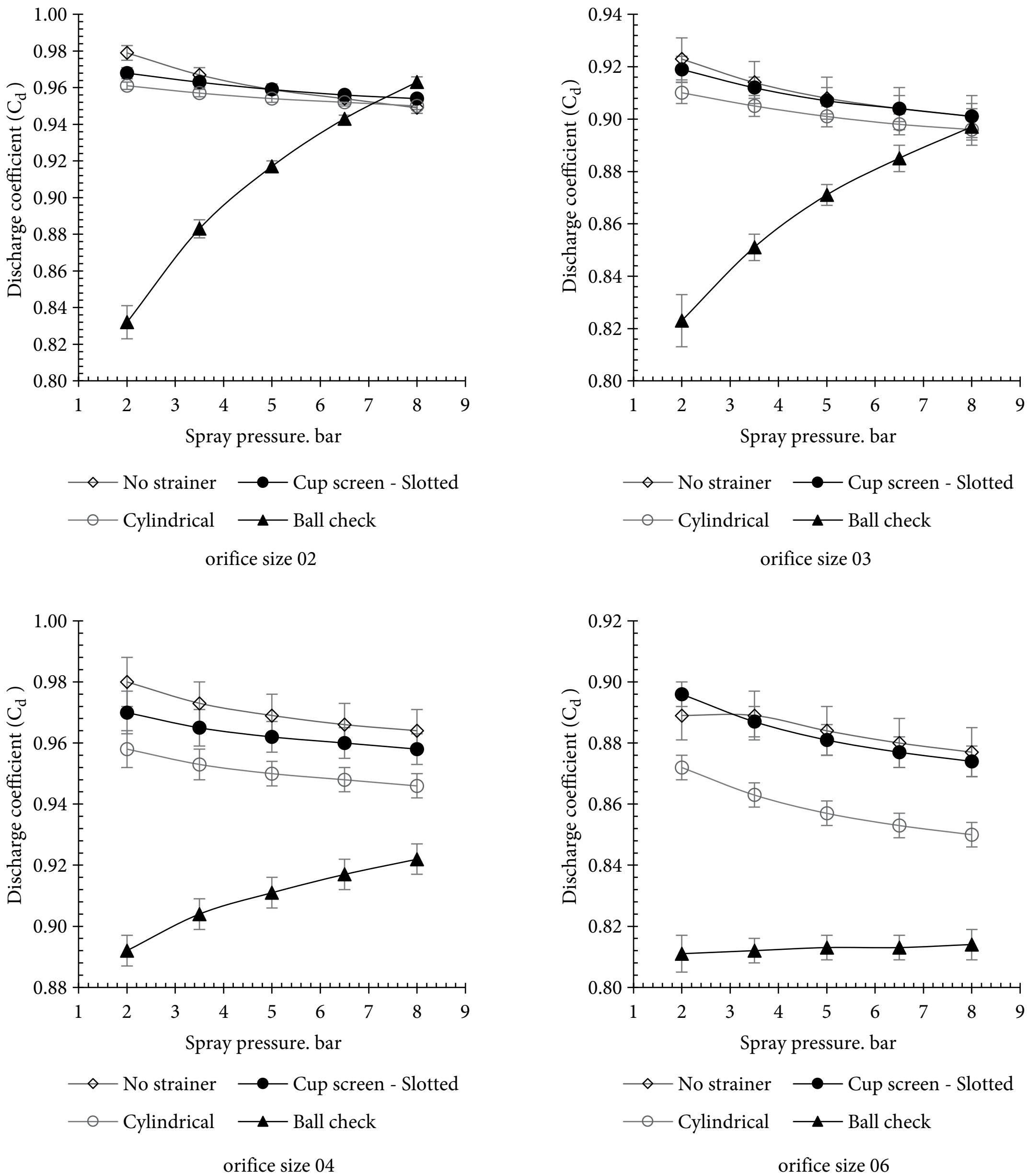


Figure 2. The influence of the strainer types on the variation of discharge coefficient (C_d, mean and standard error) corresponding to the different spray pressures for each of the nozzle orifice sizes.

The nozzle strainer types had a crucial effect on the complete atomization of droplets produced by spray nozzle. The minimum flow rate required for complete atomization with regard to the nozzle orifice sizes linearly increased as the nozzle orifice size increased. However, the minimum spray pressure required for the nozzles with different orifice sizes decreased with the increasing nozzle flow rate for each nozzle orifice size.

This study clearly presented that the cylindrical strainers and ball check strainers had a restrictive effect on the discharge of the nozzle. This effect was higher for the ball check strainers than the cylindrical strainers. It might be concluded that the cup screen and slotted strainers had no effects on the discharge characteristics, because the results concerning the discharge were similar to the nozzle without a strainer.

Nomenclature

A_o	orifice area calculated from the orifice opening generated after 3D surface modelling, mm^2
C_d	discharge coefficient
d_{eq}	equivalent orifice diameter calculated from the measured projected area, mm
d_i	nozzle inlet section diameter, m
k	orifice coefficient
L	orifice's major length, mm
n	pressure exponent
PA_c	orifice's calculated projected area, mm^2
PA_m	orifice's measured projected area, m^2
P_{min}	minimum spray pressure, bar
Q_a	actual volumetric flow rate, $m^3\ s^{-1}$
Q_i	ideal volumetric flow rate, $m^3\ s^{-1}$
Q_{min}	minimum flow rate, $l\ min^{-1}$
Q_n	nominal flow rate at 276 kPa spray pressure based on nozzle's orifice size, $m^3\ s^{-1}$ ($3.785 \times$ nominal flow rate, $(gal\ min^{-1})/60{,}000$)

U_e	liquid outlet velocity, $m\ s^{-1}$
U_i	liquid inlet velocity, $m\ s^{-1}$
V_j	liquid jet velocity, $m\ s^{-1}$
W	orifice's minor length, mm
α	V-cut angle (°)
α_c	spray angle calculated based on orifice's V-cut angle (°)
α_n	nominal spray angle (°)
ΔP	total pressure drop, Pa
ΔP_c	constant spray pressure of 2.76×10^3 Pa (equivalent to 40 psi)
θ	spray angle (°)
μ	liquid dynamic viscosity, 0.001 Pa.s
ρ_L	liquid density, 998.2 $kg\ m^{-3}$ (for spray liquid temperature of 17.5 °C)
σ	surface tension, 0.0728 $N\ m^{-1}$

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