ANALYSIS OF DROP FORMATION OVER A SPRAY NOZZLE-PLATE SYSTEM

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Abstract. *The aim of this study is to apply a quantification methodology of the drop spectrum in a spray nozzle-plate system, characterizing commercial spray nozzle-plate systems and understanding physical aspects of drop formation in nozzle-plates. The basis of the methodology is high speed filming to capture high frequency phenomena, thus acquiring image of the drops generated on the nozzle-plate and later treatment of the images for obtaining the mean drop diameters. The study of the influence of the nozzle-plate system variables on the mean drop sizes is determined by means of an experimental design. A predictive equation for the diameter of the drops is presented. By means of this methodology, it is possible to characterize the drop spectrum of the existing spray-nozzle systems and also to suggest new types of these systems.*

Keywords. *Drop spectrum, mean drop diameter, high speed recording, spray nozzle-plate, experimental design.*

1. Introduction

The aim of this study is to apply a quantification methodology of the drop spectrum in a spray nozzle-plate system, characterizing commercial spray nozzle-plate systems and understanding physical aspects of drop formation in nozzle-plates. This methodology permits analysis of parameters that influence the drop generation over a spray nozzle-plate system. An experimental investigation of drop formation mechanisms, drop diameter distributions, and spray distributions for spray nozzle-plate system was conducted. This generic type of nozzle is used for center pivot agricultural irrigation, and a fundamental knowledge of drop formation in a spray nozzle-plate system can help reduction of water and energy consumption, and therefore permits the optimization of spray nozzle-plate designs.

Reviews of drop formation mechanisms and drop size distribution for spraying are given by McCreery and Stoots (1996), van Der Geld and Vermeer (1994), and Hsing and Tankin (1996). According to these authors, the process is governed by surface tension, aerodynamic and liquid viscous forces and in all of these tests, drop diameter distributions were obtained with a phase Doppler particle analyzer, or by means of photograph techniques. Drop mean diameters are quantified.

In this article, the experimental methodology used to quantify the drop spectrum is based on high speed recording technique to capture the high frequency phenomena in order to determine drop diameter and better understand the physics question involved. Experimental methodology and experimental results are also described. To better understand how spray nozzle-plate parameters influence the drop diameter distribution, an experimental design was applied. This article concentrates on drop diameter distributions of one type of spray nozzle-plate.

2. Experimental Method and Apparatus

A spray nozzle-plate system investigated on this study is composed of an injection nozzle which projects a jet of water against a plate, as illustrated in Fig. (1). The jet is concentric to the plate and a liquid sheet forms after the plate. The liquid sheet flows in a radial direction outward from the plate, and breaks-up into drops.

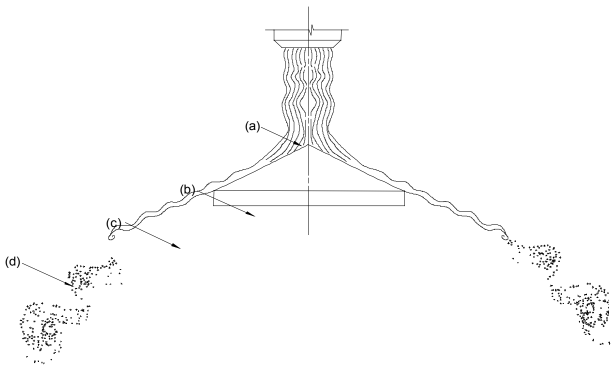


Figure 1. Spray nozzle-plate system; (a): liquid jet; (b): liquid film over the plate; (c): free liquid film; (d): drop formation.

A fundamental knowledge of drop formation in a spray nozzle-plate system is very important for the reduction of water and energy consumption, improving the uniformity of the irrigation area by reducing the undesirable effects of soil erosion and drop evaporation, thus optimizing the agricultural production. This improvement depends on the drop distribution and the physical phenomena that determine drop formation mechanisms and the drop size distribution. In this study the influence of four variables on drop diameter and on the drop size distribution were investigated: the diameter of the injection nozzle, the flow rate of the system, the nozzle-to-plate spacing, and the type of plate surface. A spray nozzle-plate system used on this study is shown in Fig. (2).

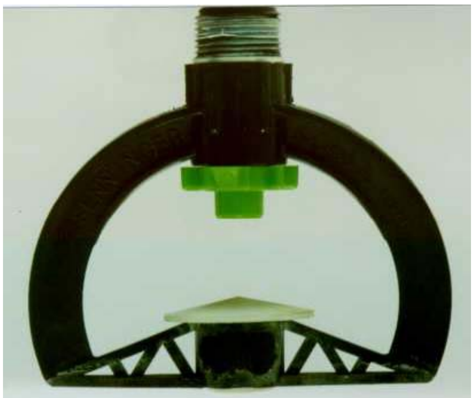


Figure 2. A typical nozzle-plate system investigated in the present study.

The experimental setup used to investigate the drop formation is shown in Fig. (3). At the start, water flows from a source to the injection nozzle which projects a jet against a conical plate and then the drops are formed. The images of the drops were captured by a high speed camera and were digitalyzed to permit treatment by software. A table of results is then obtained and transferred to software to be manipulated.

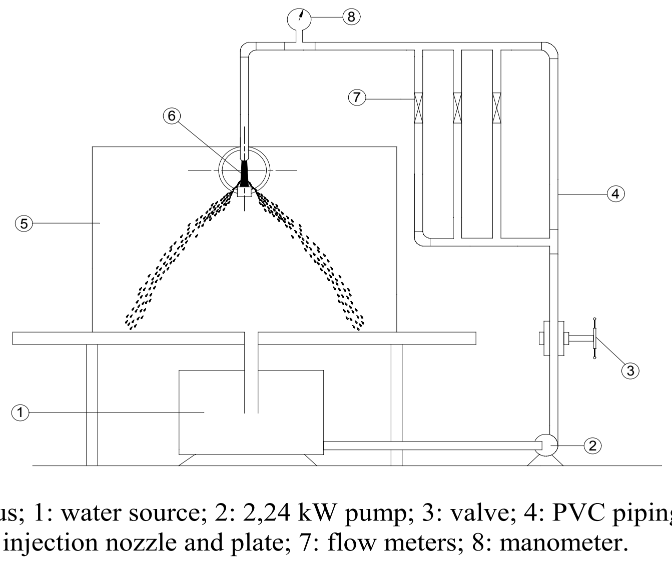


Figure 3. Experimental apparatus; 1: water source; 2: 2,24 kW pump; 3: valve; 4: PVC piping 25 mm diameter; 5: collector chamber; 6: injection nozzle and plate; 7: flow meters; 8: manometer.

A schematic diagram of experimental apparatus is shown in Fig. (4). To get the results in an unit system that is adequate to the applications, the software needs to be calibrated. For this, it is necessary to provide a reference element with the image, for example, a small sphere whose diameter is known. Therefore, when the image is taken, this reference element will appear and can be measured by the software, with which the drop size is compared.

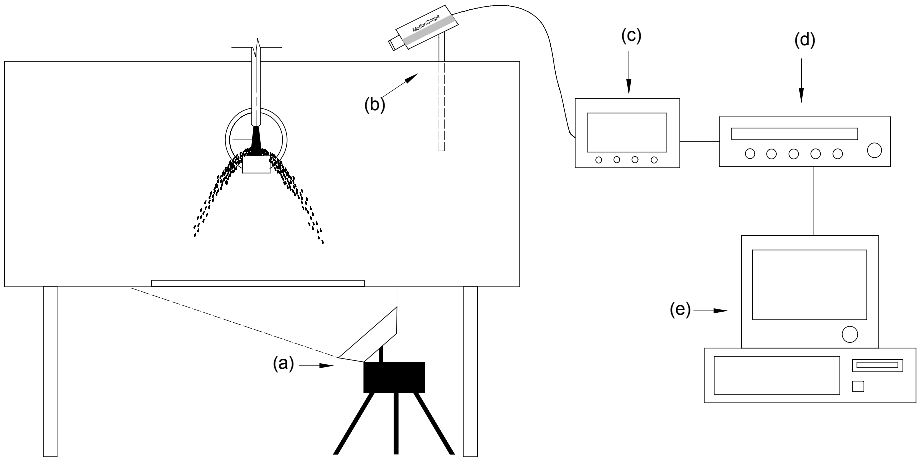
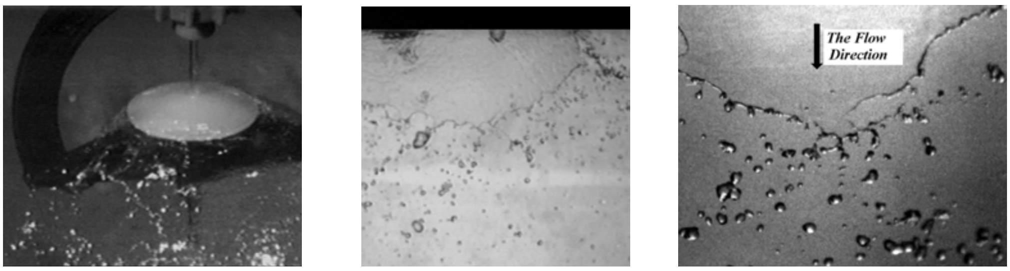


Figure 4. Schematic diagram of experimental apparatus. (a): two lamps of 1 kW; (b): high speed CCD camera; (c): camera monitor; (d): super VHS video; (e): frame grabber software (image analysis).

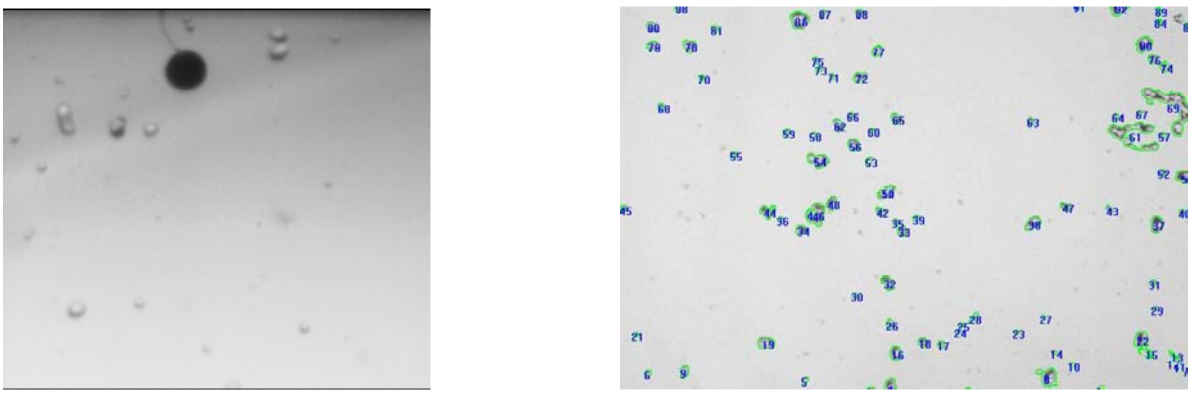
A typically drop size spectra produced by this spray nozzle-plate system and images detailing drops formation process, are shown in Fig. (5).



(a) (b) (c)

Figure 5. Sequential images of the system investigated: (a): injection nozzle and plate surface; (b): liquid sheet formed after the plate; (c): detailed image of the drops formation.

To calibrate the software in order to measure drop diameters, an image of drop spectra with a spherical body 4 mm in diameter was taken, as can be seen in Fig. (6a).



(a) (b)

Figure 6. (a): Drop spectra with a spherical body used in the calibration tool; (b): a typical image showing the drops numbered.

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In the sequence, the images of the drops were digitalyzed and, after digital filtering, it was possible to determine the drops diameters, according to the calibration system. The image showing the drops numbered is presented in Fig. (6b).

Experiments were performed to measure the effects of the control variables on a response. By using experimental design before conducts experiments, the confusing effects of experimental results can greatly help the investigator on identification and quantification of relevant variables on the process. The net effect is to increase greatly the probability that the investigator will be led along a true rather than a false path. Factorial designs are extremely useful for this purpose, especially two-level factorial designs, because they are economical and easy to use and can provide a great deal of valuable information, according to Box et al. (1978). In order to conduct the experiments and better understand the experimental results, a 2^4 factorial design was performed, according to Box et al. (1978). The levels of the 4 variables selected on this study, the diameter of the injection nozzle (d_b), the flow rate of the system (Q), the nozzle-to-plate spacing (h), and the geometry of plate, are presented in Table (1). The values appearing in Table (1) represents the maximum and minimum values concerned to the experimental setup. In the case of water flow rate, the maximum value depends on the pump capacity, which, in this study, is supplied by a 2,24 kW pump.

Table 1. Design Matrix of a Two-Level Factorial.

Variable	Level (+)	Level (-)
X_1: d_b [mm]	8.73	5.15
X_2 : Q [cm^3/s]	208.33	87.5
X_3 : h [mm]	40	24
X_4 : geometry of plate	conical	plane

Table (1) shows a 2^4 factorial experiment in which there are three quantitative variables, diameter of the injection nozzle (d_b), flow rate of the system (Q), nozzle-to-plate spacing (h) and a single qualitative variable, the geometry of plate.

3. Results

Using a two-level factorial design to estimate the main effects of the variables, one can decide what type of plate geometry will be used on the tests and the influence of interaction of variables. After the experimental runs and software treatments, the results are the mean drop diameters in an adequate unit system, mm for example. Table (2) shows the recorded data with the levels coded so that for the quantitative variables a minus sign represents the low level and a plus sign the high level, and for a qualitative variable the two levels or versions can also be conveniently coded by minus and plus signs.

Table 2. Data from a 2^4 factorial design.

Experiment	X_1	X_2	X_3	X_4	Drop Diameter [mm]
1	-	-	-	-	1.063
2	+	-	-	-	1.820
3	-	+	-	-	0.674
4	+	+	-	-	0.940
5	-	-	+	-	1.781
6	+	-	+	-	3.390
7	-	+	+	-	0.990
8	+	+	+	-	2.360
9	-	-	-	+	1.180
10	+	-	-	+	2.090
11	-	+	-	+	0.622
12	+	+	-	+	1.000
13	-	-	+	+	1.823
14	+	-	+	+	2.668
15	-	+	+	+	0.913
16	+	+	+	+	1.885

As can be seen, each line in Table (2) represents an experimental condition, or a test to be realized in the experimental setup shown in Fig. (4). The result of each test is a frame sequence with images of the drops. In this experimental investigation, 16 sets of data were acquired. Each set consisted of 10 frames resulting in a total of 160 frames. Then, after software treatment, the final result of each test is the mean drop diameter, as presented in Table (2).

The effects of the variables on the drop diameter and the significance level (α) of the variables, are presented in Table (3), and this is the final result of a statistical software.

Drop formation mechanism is governed by many parameters. An important aspect of the drop formation mechanism is the knowledge of the physical interaction between the gas and liquid phases, according to McCreery and Stoots (1996). Also, it is important to know how the flow characteristics influence the drop diameter. The flow rate and geometric conditions, like the diameter of the injection nozzle and nozzle-to-plate spacing, have an influence on the drop formation, as can be observed in Table (3), and the types of plate geometry used on the tests, do not influence the diameter of the drop.

Table 3. Significance level of the variables.

Factor	Effects	Significance Level (α)
X_1	0.888	0.0003
X_2	-0.804	0.0005
X_3	0.803	0.0006
X_4	-0.105	0.3560
$X_1.X_2$	-0.141	0.2260
$X_1.X_3$	-0.311	0.0295
$X_2.X_3$	-0.112	0.3250
$X_1.X_4$	-0.075	0.5010
$X_2.X_4$	-0.031	0.7720
$X_3.X_4$	-0.203	0.1050

As can be observed in Table (3), the variables that strongly influence the drop diameter are, in order of importance, the diameter of the injection nozzle (d_b), the water flow rate (Q) and the nozzle-to-plate spacing (h). This result was observed by a hypothesis test, where maximum probability error admitted is 5%, or, $\alpha < 0,05$. According to the results, the mean drop diameter remains the same for the two types of plate geometry investigated in this study. The qualitative variable plate geometry does not significantly influence the drop diameter ($\alpha = 0,36$). The results presented in Table (3) show that the dependence of drop diameter distribution on nozzle-to-plate spacing is less dramatic than the dependence on nozzle diameter and water flow rate.

Figure (7) shows the dependence of mean drop diameter on the injection nozzle diameter, and, as can be seen, there is a linear relation that was quantified.

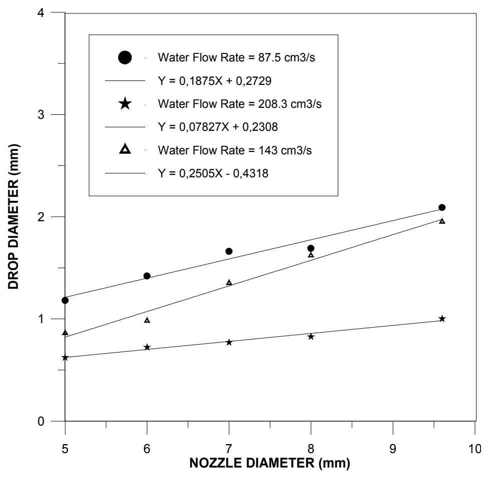


Figure 7. The effect of the nozzle diameter in the drop diameter.

After the 2^4 experimental design runs, the results indicated that it is possible to expand the analysis to other values of the three remaining variables, in order to better understand and quantify the variables interactions. To do this, a 3^3 experimental design is applied in order to quantify the dependence of mean drop diameter distribution on these variables more strongly, and to permit the quantification of this dependence by means of surface response methodology, specified in Box et al. (1978).

The variables that strongly influence the mean drop diameter are the diameter of the injection nozzle (d_b), the water flow rate (Q) and the nozzle-to-plate spacing (h). In order to get statistical consistence, one more experimental value takes place to each variable, an intermediate value between the levels (+1) and (-1), represented by level (0). These values are presented in Table (4).

Table 4: Variables levels for the 3^3 experimental design.

Variable	Level (+1)	Level (0)	Level (-1)
X_1: d_b [mm]	8.73	6.94	5.15
X_2: Q [cm^3/s]	208.33	147.94	87.5
X_3: h [mm]	40	32	24

Table (5) shown the recorded data with the levels coded after the experimental runs and software treatments, and the results are the mean drop diameters.

The design employed was a 3^3 factorial with three center points, and after the experimental runs the results are used on fitting and checking the second-degree polynomial model,

$$Y = \beta_0 + aX_1 + bX_2 + cX_3 + dX_1X_2 + eX_1X_3 + fX_2X_3 + gX_1^2 + hX_2^2 + iX_3^2 \tag{1}$$

This empirical equation has 10 parameters to be determined with the 27 experimental runs presented in Table (5).

Before attempting to interpret the fitted surface, one needs to consider whether or not it is estimated with sufficient precision. This can be done by a special application of the analysis of variance (Box, 1979). A statistical analysis of the equation parameters was done by Student's t distribution, and again the maximum probability error admitted is 5%, or, $\alpha < 0.05$. These results are shown in Table (6).

Table 5: Data from a 3^3 factorial design.

Experiment	X_1 (d_b)	X_2 (Q)	X_3 (h)	Drop Diameter [mm]
1	-1	-1	-1	1.180
2	0	-1	-1	3.136
3	+1	-1	-1	2.090
4	-1	0	-1	0.700
5	0	0	-1	1.588
6	+1	0	-1	2.538
7	-1	+1	-1	0.622
8	0	+1	-1	0.926
9	+1	+1	-1	1.000
10	-1	-1	0	2.106
11	0	-1	0	2.940
12	+1	-1	0	2.660
13	-1	0	0	0.926
14	0	0	0	2.134
15	+1	0	0	2.081
16	-1	+1	0	0.852
17	0	+1	0	1.064
18	+1	+1	0	1.641
19	-1	-1	+1	1.823
20	0	-1	+1	3.040
21	+1	-1	+1	2.670
22	-1	0	+1	0.683
23	0	0	+1	1.629
24	+1	0	+1	2.380
25	-1	+1	+1	0.913
26	0	+1	+1	0.938
27	+1	+1	+1	1.885

Table 6: Significance level of the variables.

Factors	Parameter	Significance Level
β_0	1.966	0.000
X_1	0.508	0.000
X_2	-0.656	0.000
X_3	0.121	0.2393
X_1X_1	-0.335	0.0679
X_1X_2	-0.0143	0.9076
X_1X_3	0.0325	0.7926
X_2X_3	0.0050	0.9672
X_2X_2	0.1204	0.4935
X_3X_3	-0.1704	0.3360
$R^2 = 0.80$	$F_{CALC.} = 28.10$	$F_{TAB.} = 4.76$

As can be seen in Table (6), the $F_{CALC.}$ value was greater than the $F_{TAB.}$ value for a significance level of 1%. These results can be interpreted by a hypothesis test that is the essential nature of a significance test. A criterion appropriate for testing the null hypothesis (H_0) that the model is not significance, or all the equation parameters are equal to zero against the alternative hypothesis (H_1) that they were greater than zero, or the model is significance. The results shown that the null hypothesis is discredited and a statistically significant difference has been obtained.

The equation parameters that really influence the mean drop diameter are shown in Table 7.

Table 7: Regression parameters.

Factors	β_0	X_1	X_2	X_3	X_1X_1
Parameter	1.932	0.508	-0.656	0.121	-0.336

As can be observed in Table (7), the variable that strongly influence the drop diameter is the water flow rate (X_2), followed by the diameter of the injection nozzle (X_1), and the nozzle-to-plate spacing (X_3).

Concerning to the experimental values presented in Table (5), one can note that an increase on the injection nozzle diameter (X_1), causes an increase on the mean drop diameter, while the opposite is observed in relation to the water flow rate (X_2). These results are in agreement with the work by McCreery and Stoots (1996). It was observed that an increase on the nozzle-to-plate spacing (X_3), causes an increase on the mean drop diameter, in accordance with the 2^4 experimental design.

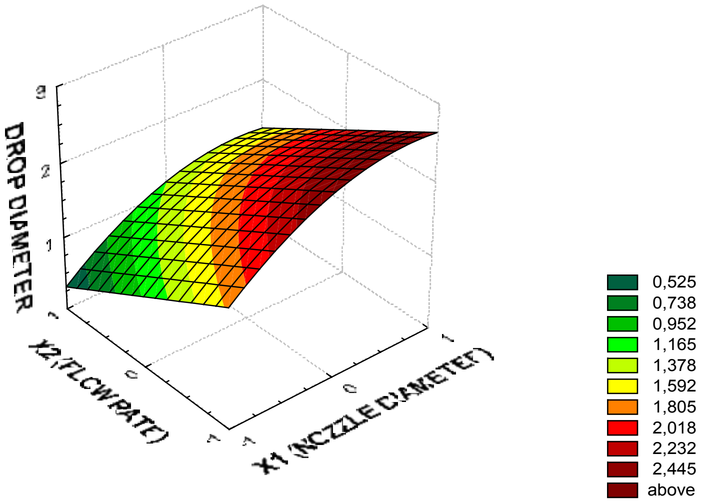
The value of 0.80 was obtained by R^2, the squared multiple regression coefficient or sample correlation coefficient, that means 80% of the data variability were explained by the equation, according to Box et al. (1978).

The regression equation obtained by the experimental results is:

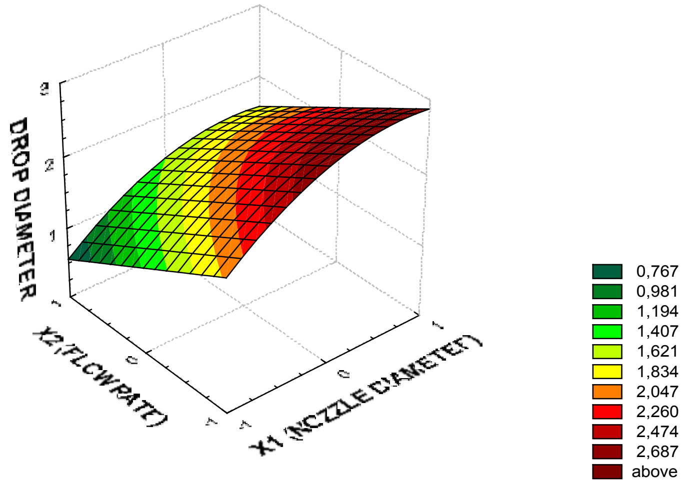
$$D_{DROP} = 1.932 + 0.508 D_{NOZZLE} - 0.656 Q - 0.336 D_{NOZZLE}^2 + 0.121 h \quad (2)$$

The regression equation permits the definition of the operational conditions to control the mean drop diameter.

Figure 8 presents a surface response that relates the variables X_1 and X_2 with mean drop diameter.



(a)



(b)

Figure 8. Surface response of variables X_1 , X_2 on drop diameter: (a): small nozzle-to-plate spacing; (b): large nozzle-to-plate spacing.

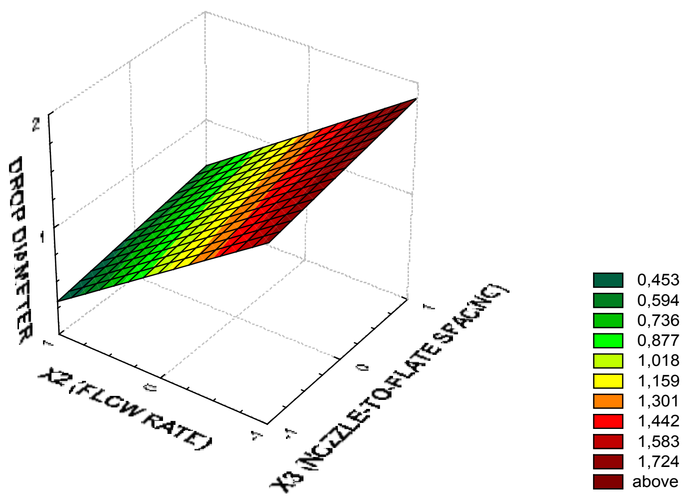
Analyzing the results presented in Fig. (8a), one can note that using intermediates values of the diameter of the injection nozzles with water flow rate close to the maximum used on the experiments, the drop diameters lies between 1 mm and 2 mm. The surface response shown that an increase on the injection nozzle diameter, the drop mean diameter increases. To operate with smallest water flow rate, to get the mean drop diameters between 1 mm and 2 mm, the surface response in Fig. (8) suggest that the injection nozzle diameter should be the smallest.

To analyze the effects of the variables nozzle-to-plate spacing (X_3) and water flow rate (X_2) on the mean drop diameter, the surface response obtained by the experimental results is presented in Fig. (9).

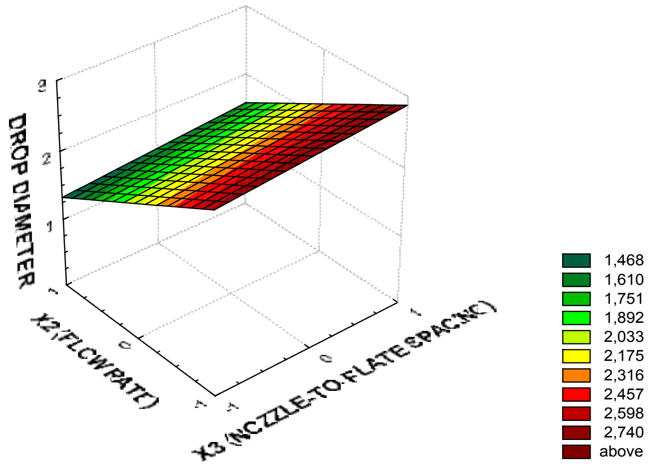
As can be seen in Fig. (9a) the mean drop diameters greater than 1 mm and smallest than 2 mm are presented when the system operates with large water flow rates. The results shown that an increase on the nozzle-to-plate spacing (X_3) causes an increase on the mean drop diameter, while an increase on the water flow rate (X_2) reduces the mean drop diameter. Modifying the injection nozzle diameter to the level (-1), the results are presented in Fig. (9b).

Figure (9a) and (9b) shown that a decrease on the injection nozzle diameter causes a decrease on the mean drop diameter and when the water flow rate (X_2) increases, the mean drop diameter decreases. The nozzle-to-plate spacing (X_3) causes a directly proportional effect on the mean drop diameter.

The influence of the variables injection nozzle diameter (X_1) and nozzle-to-plate spacing (X_3) on the mean drop diameter is presented in Fig. (10a) and (10b). The results observed in Fig. (10) shown that the mean drop diameter increases when the nozzle-to-plate spacing (X_3) increases. The same result can be obtained when the injection nozzle diameter (X_1) increases.

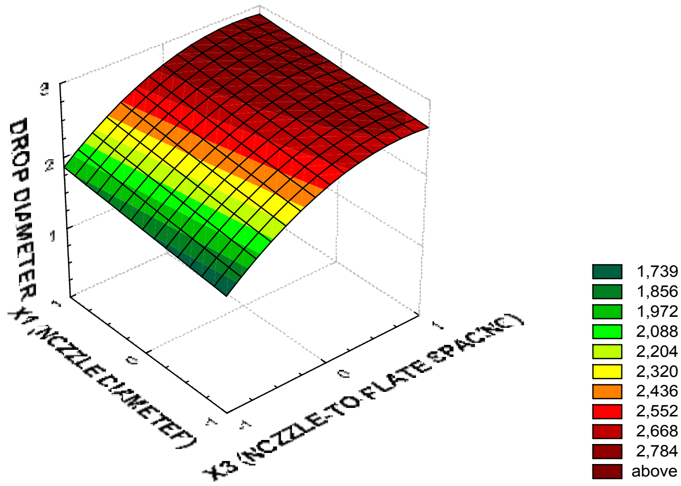


(a)

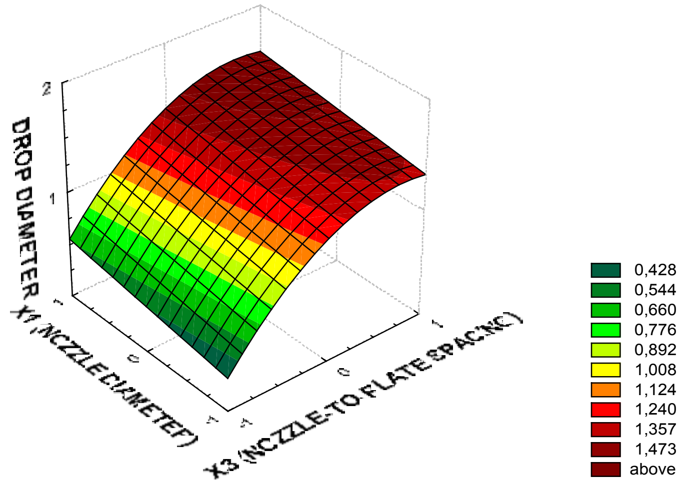


(b)

Figure 9. Surface response of variables X_2, X_3 on drop diameter: (a): small nozzle diameter; (b): large nozzle diameter.



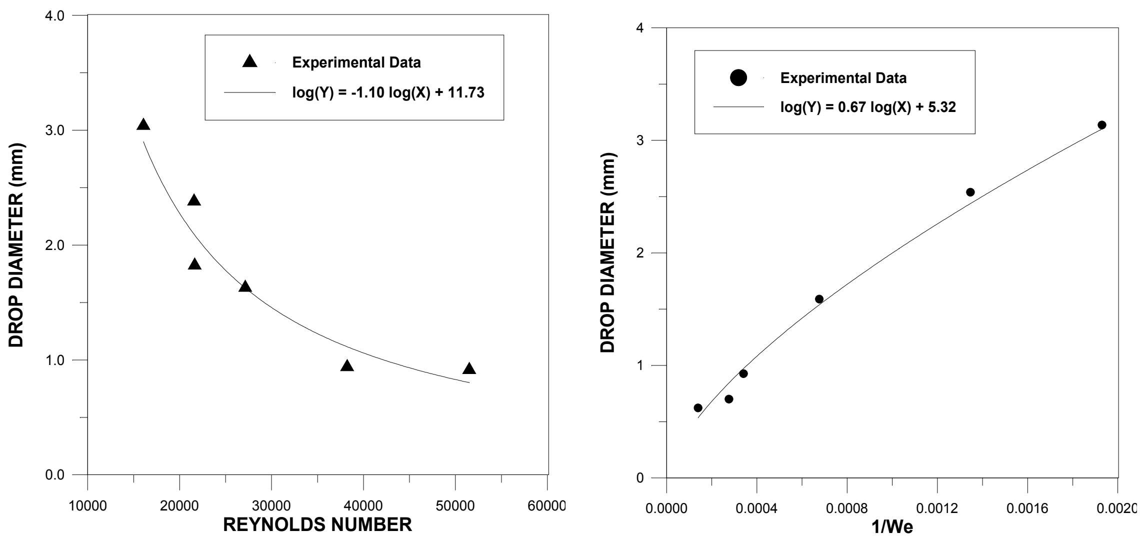
(a)



(b)

Figure 10. Surface response of variables X_1, X_3 on drop diameter: (a): small water flow rate; (b): large water flow rate.

The dependency of drop diameter distribution on admensional numbers was investigated in the present study. Considering the Reynolds number as $R_e = \rho v d / \mu$, where ρ is the fluid density, v is the fluid velocity, d is the injection nozzle diameter and μ is the fluid viscosity, the Reynolds number's influence on the mean drop diameter distribution is shown in Fig. (11a). Another important admensional number, appropriate do analyze the break up of jet regimes over nozzle systems, is the Weber number, as attested by Chigier and Reitz (1994). The Weber number relates inertial forces to superficial tension as $W_e = \rho v^2 A / \sigma\sqrt{A}$. The effect of Weber number on drop diameter was examined by varying the water exit velocity. No variations of surface tension were undertaken. The data presented in Fig. (11b) was used to establish the dependence of the mean drop diameter on the Weber number.



(a) (b)

Figure 11. Mean drop diameter dependency on: (a): Reynolds number; (b): Weber number.

As can be seen in Fig. (11a), the mean drop diameter decreases as Reynolds number increases. This is a physically consistent result, since the Reynolds number increases, atomization is achieved and smallest droplets appear.

The results presented in Fig. (11b) appoint to a condition where the mean drop diameter increases as inverse Weber number increases. This observed influence can be explained by the analysis of the forces presented on drop formation mechanisms.

4. Concluding Remarks

Drop diameter distribution data for a spray nozzle-plate system were measured using a high speed recording technique, and a mean drop diameter was calculated for each distribution.

A 2^4 experimental design was performed and the experiments quantify the influence of nozzle diameter, nozzle-to-plate spacing, water flow rate of the system and type of plate geometry on the drop diameter. A 3^3 experimental design was applied to quantify the dependence of drop diameter distribution on injection nozzle diameter, water flow rate and nozzle-to-plate spacing, by means of surface response methodology.

In general, drop diameter increases with injection nozzle diameter and decreases with increasing water flow rate. The dependence of drop diameter distribution on nozzle-to-plate spacing is less dramatic than the dependence on injection nozzle diameter and water flow rate. The plate geometry does not influence the drop diameter. The diameter of the spherical body used to calibrate the software is higher than the smallest drops obtained during the experiments.

The experiments quantify the influence of Reynolds number and Weber number on drop diameter distribution for nozzle-plate systems. The results shown that mean drop diameter decreases with Reynolds number increases and increases with the inverse of Weber number.

5. References

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