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Optimization of Swirl Effervescent Spray Dispersity via Response Surface Methodology

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Abstract

The swirl effervescent spray angle characterizes the spray dispersity. Various parameters were investigated to observe their relation to the spray angle; however, Response Surface Methodology (RSM) named Box-Behnken Design (BBD) was used as an approach to reduce the number of experimental runs and formulate an empirical model. The effect of three independent variables (swirl vane angle, gas volume flow rate, and discharge orifice diameter) on the spray angle was investigated. An empirical model was developed and verified. It was found that geometrical variables (swirl vane angle & discharge orifice diameter) are the most influential variables in characterizing a spray angle emanating from a swirl effervescent atomizer. The obtained results are important for the in-depth understanding of the swirl effervescent atomization mechanics.

Discipline: Mechanical Engineering, Mathematical modelling

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1 Introduction

A swirl effervescent atomizer is an example of a hybrid atomizer. This type of atomizer overcomes the narrow spray angle of an effervescent atomizer with the introduction of swirling flows and the need for high liquid injection pressure with the gas energy spray formation mechanism by the effervescent atomizer. Although the gas energy spray formation mechanism requires an external gas supply, the effervescent atomizer only requires low liquid flow rates for bubbling the bulk liquid. This feature is dissimilar to any other gas energy such as airblast atomizers and other twin-fluid atomizers, which impart kinetic energy of gas to shatter the liquid jet into ligaments and droplets. This has made effervescent atomization more advantageous than other twin-fluid atomizers (Hammad et al., 2021).

A spray angle is an essential feature for a variety of applications. A larger spray pattern of a pressure-swirl atomizer paired with a slower velocity field will allow for more uniform mixing of the intake gases than an impinging jet atomizer in gas cooling applications (Schick & Knasiak, 2000). In typical direct injection diesel engines, spray angle is an essential parameter that controls fuel evaporation, combustion, and emissions (Gad et al., 2022). A larger spray angle is required in automatic hand sanitizer (Isa et al., 2019). The angle of the spray profile is known as the spray angle as shown in Figure 1.

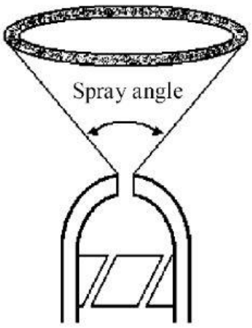

Figure 1: Schematic of spray angle (adapted from Hamid & Atan, 2009).

Response Surface Methodology (RSM) involves regression analysis, statistical and mathematical-based study, and experimental examinations. RSM utilizes a sequence of experiments to establish the optimal response of the system or determine the range of operational factors to extend the process improvement (Paturi et al., 2021). This article presents the optimization of swirl effervescent spray angle using RSM, in which, to the best of the author's knowledge, no attempt has been made previously. Among the available RSM, BBD is selected by considering the reduction of experiments to 15 experiments from 27 experiments (considering three variables with three levels each). BBD is also a good choice considering that this design excludes any experiment performed under extreme conditions, for which unsatisfactory results might occur (Haque, 2022).

2 Nomenclatures

d_o	Discharge orifice diameter, mm
Q_G	Gas volume flowrate, l/min
X_n	Uncoded variables
x_n	Coded variables
	Greek Symbols
α	Constant
β_n	Regression coefficients
γ	Swirl vane angle, °
	Abbreviations
Adj MS	Adjusted Mean Squares
Adj SS	Adjusted Sums of Squares
ANOVA	Analysis of Variance
BBD	Box-Behnken Design
CI	Confidence Interval
DF	Degree of Freedom
F	F-value

P	P-value
PI	Prediction Interval
RSM	Response Surface Methodology
Seq SS	Sequential Sums of Squares

3 Literature Review

The atomizer geometries are among the significant parameters affecting the spray angle. Gad et al. (2022) investigated the effect of discharge orifice diameter (d_o) on the spray angle emanating from a swirl atomizer and observed a directly proportional relation. Jedelsky and Jicha (2010) varied the intensity of the swirl-generating vane and discovered that a more intense swirl-generating vane produces a larger spray angle. Ghaffar et al. (2015a) observed the combined effect of swirl-generating vane intensity and d_o result in a wide spray angle discharging from a swirl-effervescent atomizer.

Operating conditions are also another important parameter in characterizing a spray angle. Dafsari et al. (2019) and Najafi et al. (2020) found that an increase in Reynolds number (Re) widens the spray angle discharge from a swirl atomizer. Lan et al. (2014) investigated both the pressure drop and geometries effect of the spray angle and found certain geometries may result in a significant decrease in spray angle with pressure drop. Jedelsky and Jicha (2010) observed the inversely proportional influence of gas volume flow rate on the spray angle. However, Jedelsky and Jicha (2010) also discovered that a further increase in the gas volume flow rate with a gas-to-liquid mass flow rate ratio exceeding 15% diminishes the influence of the spray angle.

4 Method

4.1 Atomizer Geometries and Operating Principles

The swirl effervescent atomizer under investigation includes an inside-out gas injection arrangement that allows gas bubbles from the aeration tube to mix with the bulk liquid in the mixing chamber. The atomizer features two inlets: one for liquid and one for gas. Liquid enters the mixing chamber by the side inlet, while gas enters through the middle inlet. The gas-liquid combination is spun by the swirl-generating vanes before departing the atomizer through the discharge orifice. To allow for internal flow viewing, the atomizer is built of Perspex. To maintain good transparency, the inside sides of the atomizer are surface finished. This aids in the visualization of two-phase flow mixtures in the atomizer. Figure 2 depicts the swirl effervescent atomizer schematic.

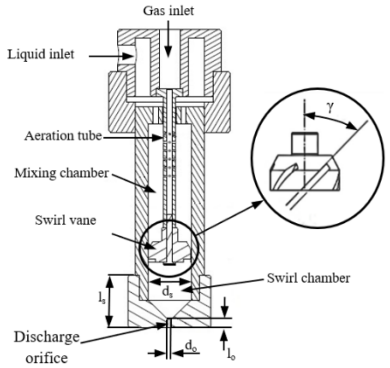

Figure 2: Schematic of swirl effervescent atomizer.

4.2 Experimental Test-Rig

The atomizer performance test is conducted with an experimental test rig. Water is employed as the working fluid, with nitrogen acting as an atomization aid. Figure 3 depicts a line schematic of the experimental test setup. Water is delivered from the water supply tank to the atomizer via the waterline using a pulseless centrifugal pump. A ball valve placed at the pump's outlet controls the amount of water that flows out of it. The amount of gas that flows from the nitrogen gas cylinder to the atomizer is controlled by a pressure regulator. The system's water and gas flow rates are measured using water and gas flow transmitters, respectively. Globe valves are used to control the flow of both water and gas. A water strainer is added anterior to the water flow transmitter intake to prevent undesirable debris from flowing through the meter and causing it to malfunction. Water and gas injection pressures are measured using digital pressure gauges. Water and gas flow check valves are fitted at the atomizer's intake to allow unidirectional flow. The atomizer is positioned vertically downward to spray water into the water collection tank. A submersible pump returns the water to the water supply tank.

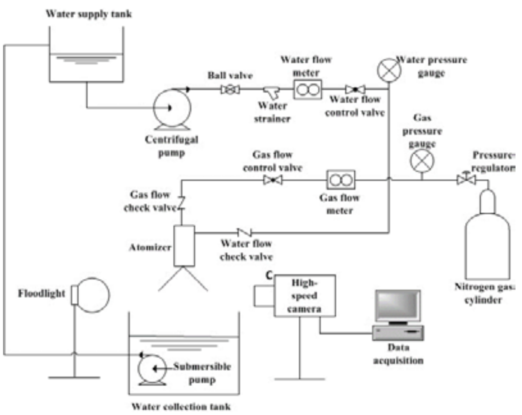

Figure 3: Line diagram of the experimental test rig.

A high-speed camera captures the video recordings of the resultant sprays produced with 800x600 video resolutions at 1000 frames per second. The shutter speed is set to a maximum value which results in an exposure of 5μs. Shadowgraph technique is applied in acquiring the resultant sprays video recordings. The acquisition method of the spray angle is based on the stages described by Ghaffar et al. (2015b).

4.3 Experimental Design

The swirl effervescent spray angle is determined using a BBD. The independent variables used are swirl vane angle, gas volume flow rate, and discharge orifice diameter. The selection of these parameters is considered based on the most significant parameters affecting the spray angle of swirl and effervescent atomization as reviewed by Ghaffar et al. (2012). The levels of each variable are shown in Table 1 and the matrix of the experiments is in Table 2.

4.4 Response Surface Regression

Response surface regression analysis is conducted using Minitab software. The regression model for the three independent variables (x_1, x_2, and x_3) can be presented in a general form:

$$Spray\ angle = \alpha + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_1^2 + \beta_5 x_2^2 + \beta_6 x_3^2 + \beta_7 x_1 x_2 + \beta_8 x_2 x_3 + \beta_9 x_3 x_1 \quad (1).$$

where β1 to β9 represent regression coefficients and α is a constant.

Table 1: Levels of Independent Variables Selected.

Variables	Symbols		Coded levels		
	Uncoded	Coded	-1	0	+1
Swirl vane angle, γ (°)	X1	x1	30	45	60
Gas volume flowrate, QG (l/min)	X2	x2	0.2	0.4	0.6
Discharge orifice diameter, do (mm)	X3	x3	1.5	2.0	2.5

Table 2: BBD Experimental Matrix.

Run Order	Coded variables			Uncoded variables		
	x_1	x_2	x_3	X_1	X_2	X_3
1	-1	0	+1	30	0.4	2.5
2	+1	0	-1	60	0.4	1.5
3	0	0	0	45	0.4	2
4	-1	-1	0	30	0.2	2
5	+1	0	+1	60	0.4	2.5
6	+1	-1	0	60	0.2	2
7	-1	+1	0	30	0.6	2
8	+1	+1	0	60	0.6	2
9	0	0	0	45	0.4	2
10	0	+1	+1	45	0.6	2.5
11	0	+1	-1	45	0.6	1.5
12	-1	0	-1	30	0.4	1.5
13	0	-1	+1	45	0.2	2.5
14	0	-1	-1	45	0.2	1.5
15	0	0	0	45	0.4	2

5 Result and Discussion

5.1 RSM Modeling

Response surface regression for the spray angle versus the three independent variables, i.e., swirl vane angle, gas volume flow rate, and discharge orifice diameter is conducted using data in coded units. Accordingly, an analysis of variance (ANOVA) is performed. The objective of ANOVA is to identify the RSM model that best fits the whole data from which the data are tested (Paturi et al., 2021). The following results are calculated by ANOVA as shown in Table 3.

It is evident from Table 3 that linear and square regressions are significant to be included in the model, but interaction is found to be insignificant. This can be portrayed by the p-value < 0.05. Linear has a p-value of 0.003. Square regression has a p-value of 0.058, which is just slightly higher than 0.05, but this regression has been included considering one square term has a p-value of 0.021.

Re-analysis is conducted with the exclusion of interaction terms. New ANOVA for a reduced spray angle model is shown in Table 4. The estimated regression coefficient for uncoded units is obtained and shown in Equation 2. The relationship between the predicted and observed spray angle is shown in Table 5.

$$Spray\ angle = -15.205 + 1.886X_1 + 23.362X_2 - 22.316X_3 - 0.017X_1^2 - 29.445X_2^2 + 6.815X_3^2 \quad (2).$$

A fitted line plot is used to compare how well the known data is within the fitted line. A linear fitted line plot for the spray angle is shown in Figure 4. The spray angle regression is plotted alongside a 95% confidence interval (95% CI) and 95% prediction interval (95% PI). An experimental point (red dot in the plot) situated within either 95% CI or 95% PI portrays a good fit. Another tool for the model goodness of fit is the standard error in regression (S). The value of S approaching 0 indicates a small prediction error (Warner, 2013; Minitab Blog Editor, 2014). This spray angle regression has a value of S = 3.444 which means that the average distance of the experimental points from the fitted line is only 3.444%.

Table 3: ANOVA for spray angle model.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	382.307	382.307	42.479	8.9	0.013
Linear	3	300.89	300.89	100.297	21.02	0.003
X1	1	252.001	252.001	252.001	52.82	0.001
X2	1	0.012	0.012	0.012	0	0.962
X3	1	48.876	48.876	48.876	10.24	0.024
Square	3	71.483	71.483	23.828	4.99	0.058
X1*X1	1	54.403	52.751	52.751	11.06	0.021
X2*X2	1	6.363	5.122	5.122	1.07	0.348
X3*X3	1	10.717	10.717	10.717	2.25	0.194
Interaction	3	9.934	9.934	3.311	0.69	0.594
X1*X2	1	0.332	0.332	0.332	0.07	0.802
X1*X3	1	7.148	7.148	7.148	1.5	0.275
X2*X3	1	2.454	2.454	2.454	0.51	0.505
Residual Error	5	23.855	23.855	4.771		
Lack-of-Fit	3	17.158	17.158	5.719	1.71	0.39
Pure Error	2	6.698	6.698	3.349		
Total	14	406.162				

Table 4: ANOVA for reduced spray angle model.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	6	372.373	372.373	62.062	14.69	0.001
Linear	3	300.89	300.89	100.297	23.75	0
X1	1	252.001	252.001	252.001	59.66	0
X2	1	0.012	0.012	0.012	0	0.959
X3	1	48.876	48.876	48.876	11.57	0.009
Square	3	71.483	71.483	23.828	5.64	0.023
X1*X1	1	54.403	52.751	52.751	12.49	0.008
X2*X2	1	6.363	5.122	5.122	1.21	0.303
X3*X3	1	10.717	10.717	10.717	2.54	0.15
Residual Error	8	33.789	33.789	4.224		
Lack-of-Fit	6	27.092	27.092	4.515	1.35	0.485
Pure Error	2	6.698	6.698	3.349		
Total	14	406.162				

Table 5: Experiment and prediction spray angle.

RunOrder	Coded variables			Spray angle		Error (%)
	x_1	x_2	x_3	Experiment	Prediction	
1	-1	0	+1	20.547	17.695	13.878
2	+1	0	-1	23.799	23.977	0.747
3	0	0	0	25.023	22.912	8.435
4	-1	-1	0	12.551	12.381	1.355
5	+1	0	+1	28.266	28.920	2.315
6	+1	-1	0	25.185	23.606	6.270
7	-1	+1	0	11.301	12.303	8.871
8	+1	+1	0	22.782	23.528	3.276
9	0	0	0	21.944	22.912	4.412
10	0	+1	+1	24.864	25.871	4.051
11	0	+1	-1	23.684	20.928	11.638
12	-1	0	-1	10.733	12.752	18.811
13	0	-1	+1	24.759	25.949	4.805
14	0	-1	-1	20.446	21.005	2.735
15	0	0	0	21.770	22.912	5.247

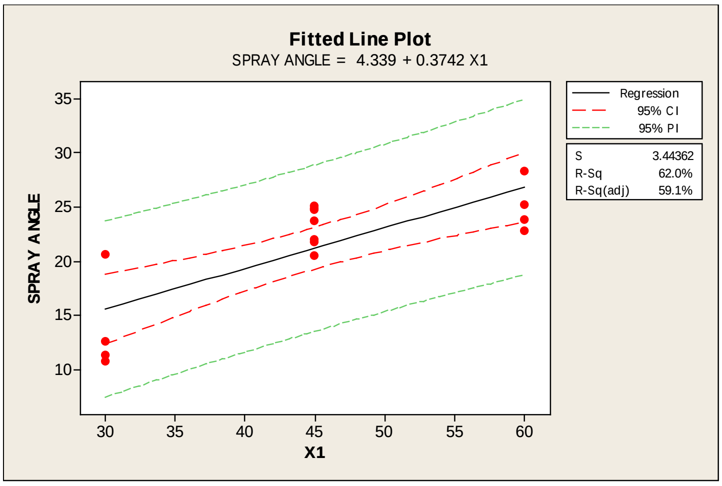

Figure 4: Fitted line plot for spray angle.

5.2 Response Surface Analysis

Contour plots showing the relation of swirl vane angle (X_1), gas volume flow rates (X_2), and discharge orifice diameter (X_3) are depicted in Figure 5 to Figure 7, respectively. It is observed that both swirl vane angle and discharge orifice diameter have a more significant effect on spray angle than gas volume flow rate. The spray angle does not portray a significant increment with the increase of gas volume flow rate as depicted by the unchanged colour in Figure 5 and only a slight change of colour in Figure 6.

The contour plot features both geometrical variables, as in Figure 7, which seems to visualize a significant effect of swirl vane angle and discharge orifice diameter on spray angle. The widest spray angle can be seen at the highest setting for both variables. This is not observed in Figure 5 and Figure 6, as the widest spray angle can be obtained even at the lowest gas volume flow rate. Significant effects of geometrical variables on spray angle are also previously reported by Gad et al. (2022) and Lan et al. (2014). A less substantial effect of gas flow rate is also reported for a twin-fluid atomizer by Jedelsky and Jicha (2010).

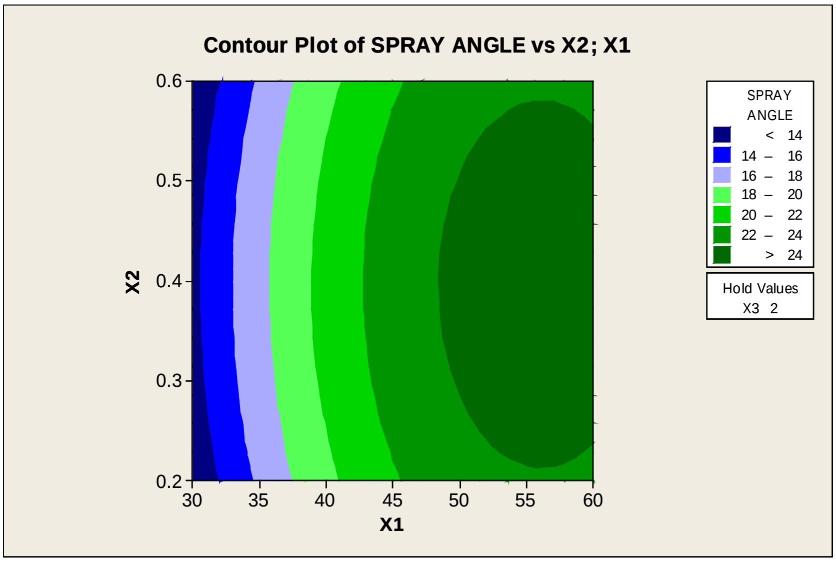

Figure 5: Contour plot of predicted spray angle on the effect of swirl vane angle and gas volume flow rate.

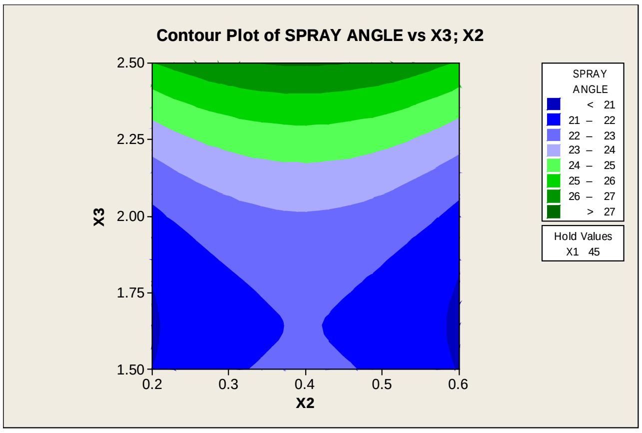

Figure 6: Contour plot of predicted spray angle on the effect of gas volume flow rate and discharge orifice diameter.

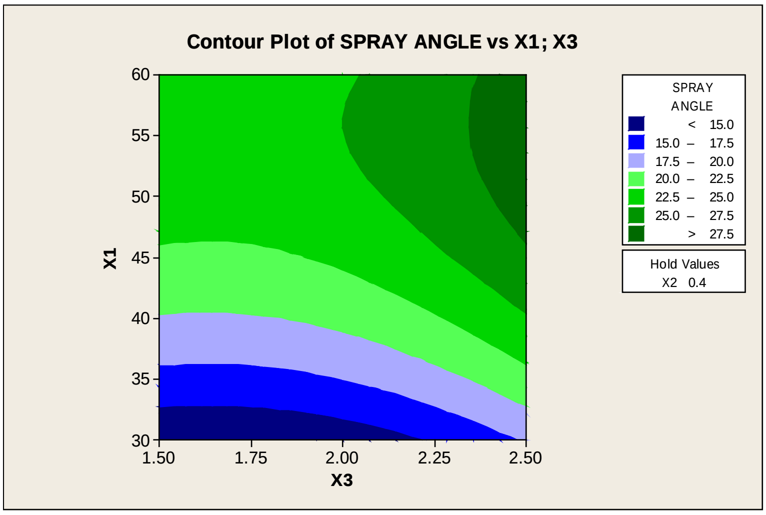

Figure 7: Contour plot of predicted spray angle on the effect of swirl vane angle and discharge orifice diameter.

6 Conclusion

The spray angle of a swirl effervescent atomizer is investigated using RSM for optimization. An empirical model for the spray angle in terms of swirl vane angle, gas volume flow rate, and discharge orifice diameter are developed. The spray angle is plotted against a fitted line plot to compare how well the prediction data is within the fitted line. The standard error in regression (S) assists in determining the prediction error and S is found to be only 3.444% which indicates a small prediction error. Among the three independent variables, geometrical variables are observed to have a more significant effect on spray angle and could be the candidate factors to optimize the spray angle.

7 Availability of Data and Material

Data can be made available by contacting the corresponding author.

8 Acknowledgement

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