Mathematical Model of SMD of Hydrodynamic Ultrasonic Atomizing Nozzle Based on Orthogonal Design

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Mathematical Model of SMD of Hydrodynamic Ultrasonic Atomizing Nozzle Based on Orthogonal Design

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Abstract: The hydrodynamic ultrasonic atomization nozzle has excellent atomization performance and has a wide range of applications in the field of spray dust reduction. A mathematical model the SMD of the nozzle was established to evaluate the SMD of such nozzles using the custom-designed spraying experiment platform and orthogonal design methods. The interaction between the SMD of the nozzle and the three influencing factors, i.e., air pressure, water pressure and outlet diameter were obtained. Through range analysis, the primary and secondary order of the three parameters affecting SMD of the nozzle is: air pressure > water pressure > outlet diameter. On this basis, a mathematical model was constructed using a multivariate nonlinear regression method to estimate the SMD of the nozzle. The predicted values of the SMD of the nozzle by the multivariate nonlinear regression mathematical model were basically consistent with the experimental results, with an average relative error of only about 5%. Thus the established mathematical model in this paper can be used to predict and calculate the droplet size for hydrodynamic ultrasonic atomizing nozzles.

Key words: spray dust reduction; hydrodynamic ultrasonic atomizing nozzle; droplet size; orthogonal design; mathematical model

1. Introduction

A large amount of dusts are produced from mining, metal smelting and other production activities (Rasmussen et al., 2013; Tatyana et al., 2019; Chen et al., 2018; Han et al., 2018). The health and safety of workers who are exposed to high dust concentrations for long periods of time will be at a serious risk (Kumia et al., 2014; Li et al., 2020; Inoka et al. 2019; Ji et al., 2016). According to the regulation from the National Health Committee of China, at production sites, the 8-hour weighted average concentrations of total dust and respirable dust should be lower than 4.0 mg/m³ and 2.5 mg/m³, respectively. Meeting this regulation is a challenge for most production companies (Han et al., 2020b; Liu et al., 2020; Wang et al., 2019a; Xiu et al., 2019; Cheng et al., 2016). Nowadays, various production enterprises have adopted a large number of effective dust protection measures; however, the situation of occupational disease in China is still severe, and pneumoconiosis is still the most serious occupational disease in China. As of the end of 2019, China had reported more than 995,000 cases of occupational diseases, and pneumoconiosis accounted for almost 89.7% of the total number of cases (Hu et al., 2020; Zhou et al., 2020; Cheng et al., 2020).

Spraying is one of the most commonly used dust management technologies in industrial fields (Xu et al., 2018; Han et al., 2020c). In spraying-based dust reduction, the pressure nozzles are generally used to achieve water atomization (Hu et al., 2019; Bao et al., 2020; Liu et al., 2018). However, due to the limited water supply pressure, the atomization effect of the pressure nozzles is often unsatisfactory, and the dust removal efficiency is generally low. Moreover, the traditional pressure nozzle consumes a large amount of water, which causes a certain degree of pollution to the industrial workplace (Wang et al., 2019b, 2019c, 2019d; Zhou et al., 2019b). Ultrasonic atomization uses ultrasonic waves to break up liquid into fine droplets. Compared with conventional pressure atomization, the advantages of ultrasonic atomization include low water pressure requirements, small amount of water consumption, and high dust removal efficiency (especially for respiratory dust). According to different working principles and internal structures, ultrasonic atomizing nozzles can be classified into two categories: piezoelectric atomizing nozzle and hydrodynamic atomizing nozzle. Hydrodynamic ultrasonic atomizing nozzles are mostly utilized in industrial dust removal sites. Hydrodynamic ultrasonic atomizing nozzles use a resonant cavity to convert the high-speed fluid kinetic energy at the nozzle outlet into mechanical energy with wavy vibration, thereby generating ultrasonic waves (Dobre et al., 2002;

Kudo et al., 2017).

In 1927, the ultrasonic atomization phenomenon was first discovered and preliminarily analyzed by Loomis and Woods (1927). In the middle of the 20th century, many scholars studied the dependence of the droplet size on the vibration frequency. A function of the droplet size on the vibration frequency was established. In addition, it was pointed out that the surface tension wave was the primary cause for the formation of fine particles during the atomization process. In order to validate the relationship between the droplet size and the surface tension wave, Lang (1962) obtained the formulas between the median particle size and relevant factors such as the surface tension in the low frequency working environment through experiments. Sarohia et al. (1979) proposed three modes of the resonant cavity, and provided a clear classification and summary of the resonant mechanism of the resonant cavity, which further improved the resonant mechanism of the hydrodynamic ultrasonic nozzle. Based on the above three modes, Sobieraj et al. (1991) analyzed the vibration of the resonant cavity and the influence of the resonant mode by studying the nozzle outlet and the structure of the resonant cavity. In the 21st century, the numerical simulation technology has been developed rapidly, and the combination of numerical simulation and experiments has been widely used. Hamed et al., (2003), Narayanan et al (2009), and Kim et al. (2018) have successively performed numerical simulation studies of the unsteady flow in the resonant cavity of the hydrodynamic ultrasonic nozzle. The results further enriched the researches on the influencing factors for the working mode of the resonant cavity and determined the generation location of ultrasonic.

China's research on hydrodynamic ultrasonic nozzles started late, but many scholars have performed extensive experimental and numerical simulation studies. Zhang et al. (2007, 2010) analyzed the principle and characteristics of hydrodynamic ultrasonic atomization, and examined the variation law of atomization quality with operating parameters and structural parameters. Sun (2004) experimentally investigated the variation of acoustic parameters with the structure parameters of nozzles and established relevant empirical formulas. Zhang et al. (2002) analyzed the ultrasonic atomization performance of water using orthogonal experiments. The results showed that the number of droplets with the size smaller than 50 μm can be used as an index for the optimal parameter of the nozzle. Using this index, the amount of water became the main influencing factor. In addition, a mathematical model for ultrasonic atomization performance was established through regression analysis of experimental data. Meanwhile, some scholars also used the fluid dynamics software ANSYS FLUENT to simulate the internal flow field, external flow field, and atomization performance of the fluid-medium ultrasonic atomizing nozzle, and to analyze the pressure and velocity vector distribution of the droplet field (Zhang et al., 2017; Li et al., 2017). Li et al. (2017, 2018) and Gao et al. (2017) designed an ultrasonic atomizing nozzle with the new structure, analyzed the influence of the structure parameters of the resonant cavity and operating parameters of the nozzle on the internal flow field and atomizing performance of the ultrasonic nozzle, and calculated the relationship between the cavity structure and sound pressure.

In summary, in the previous studies, scholars have focused on the flow field mode in the resonant cavity and ultrasonic frequency, and thoroughly studied the atomization mechanism of the hydrodynamic ultrasonic nozzle. Meanwhile, some scholars have investigated the droplet size of this type of nozzle, and obtained simple prediction mathematical models for the droplet size. However, in the existing mathematical models, the influencing factors for the droplet size were not completely considered. In addition, the established droplet prediction model cannot be applied to the program development in engineering sites. In order to fill the gaps in existing research, this study analyzed the changes the SMD of the nozzle with three parameters, i.e., air pressure, water pressure and outlet diameter using orthogonal experimental design method. A Malvern real-time high-speed spray particle size analyzer, an intelligent electromagnetic flow meter, an air mass flow meter and a high-performance camera were utilized in the study. Then a mathematical model was constructed using a multivariate nonlinear regression analysis method to estimate the nozzle SMD, providing an effective tool for the parameter prediction for ultrasonic atomizing nozzle.

2. Experimental system and scheme

2.1. Experimental system

In this study, the BL-CSBPZ-SS1.2 hydrodynamic ultrasonic atomizing nozzle produced by Jining Bolin Spraying Equipment Co., Ltd., China was used. The droplet flow was in a solid cone shape. The ultrasonic atomizing nozzle was mainly composed of a water inlet, an air inlet, a spray outlet, a mixing chamber and a resonance cavity. Both air inlet and water inlet had the inner diameter of 12.0 mm, and the specification of the connection was 0.5-inch internal thread. The exit diameter was in the range of 0.8 ~ 2.0 mm, as shown in Fig. 1. The water inlet was located at the bottom of the nozzle, while the air inlet was arranged on the side of the nozzle, and the resonance cavity (ultrasonic generator) was located at the front of the nozzle outlet. The compressed air and low-speed water flow collided in the mixing chamber to achieve the primary atomization (initial atomization). Then the gas-liquid two-phase flow was sprayed from the nozzle outlet at a high speed. The impulse of the fluid excited the ultrasonic generator to generate ultrasonic waves, which led to the secondary atomization of water.

Fig. 1. The ultrasonic atomizing nozzles used in experiment.

As shown in Fig. 2, the experimental platform for the ultrasonic atomization nozzle consisted of a pump, a water tank, a control cabinet, an air compressor, a Malvern real-time high-speed spray particle size analyzer, a frequency converter, an intelligent electromagnetic flow meter, an air mass flow meter, a digital manometer and some related pipes and valves. The output water pressure of the pump was adjusted by a frequency converter. The water supply pressure was measured by a digital manometer. The water flow rate was measured by an intelligent electromagnetic flow meter. The air pressure was controlled by a pressure reducing valve. The air flow rate was measured by an air mass flow meter. The distribution of droplet size in the droplet field was monitored by a high-speed spray particle size analyzer in real time (Wang et al., 2019e, 2019f).

Fig. 2. The experimental platform.

2.2. Experimental scheme

In this study, the orthogonal design method was used to analyze the atomization performance of the ultrasonic atomization nozzle. Orthogonal experimental design uses the minimum number of tests to analyze multiple factors and levels, and can achieve the equivalent results of a large number of comprehensive experiments. Before the orthogonal experiment was conducted, the experiment scheme was determined through the orthogonal table (Wang et al., 2019g).

2.2.1. Factors and levels of orthogonal experiment

The atomization characteristics of a nozzle typically consist of flow rate and droplet size. The flow rate of hydrodynamic ultrasonic atomizing nozzles includes both air flow rate and water flow rate. Since the diameter of droplet particles was not uniformly distributed, the average diameter of the droplet group was used to represent the droplet size. At present, there are various methods for calculating the average particle diameter of droplets. The mass median diameter (MMD) and Sauter average diameter (SMD) were most commonly used parameters for the droplet size. In this study, SMD was used as an evaluation index for the fineness of droplets.

In the spraying-based dust reduction system at the engineering sites, both the atomizing medium and the external environment were relatively constant. For certain types of fluid-medium ultrasonic atomizing nozzles, the influencing factors of the atomizing parameters include air pressure (p_{air}), water pressure (p_L), and outlet diameter (d). Therefore, air pressure, water pressure, and outlet diameter were taken as the three factors of orthogonal design. Based on previous field surveys and actual measurement, the level ranges of these three factors were determined by comprehensive considering dust reduction efficiency, water consumption and site conditions. An orthogonal experiment table was designed using the three factors and the determined levels of the factors. At the same time, in order to highlight the uniformity of the selected values and the gap of the results, the experimental scheme was designed with a fixed interval. Each factor was set to 5 levels, and the "three factors, five levels" L25 (5^3) orthogonal design method was used in the study. The factors and their levels in the orthogonal experimental are shown in Table 1.

Table 1 Factors and levels in the orthogonal experimental.

NO. of levels	Influence factor		
	$p_{\text{air}}/\text{MPa}$	P_L/MPa	d/mm
1	0.2	0.2	0.8
2	0.3	0.3	1.0
3	0.4	0.4	1.2
4	0.5	0.5	1.5
5	0.6	0.6	1.8

2.2.2. Experimental method for atomization parameters

The orthogonal experiment design scheme is shown in Table 1. This orthogonal experiment design was used to study the atomization characteristics of the ultrasonic atomization nozzle, including water flow, air flow and droplet size. The air flow rate was measured by a D07-60B Mass Flow Controller, and the water flow rate was measured by a YY-LED15K4C electromagnetic flow meter. In addition, the droplet size was measured by a Malvern droplet size analyzer, which used the line measurement principle. Briefly, using the Malvern droplet size analyzer, the distribution of droplet particle size along the laser beam can be obtained. In this experiment, the data were obtained from the droplets located 50 cm in front of the nozzle outlet.

3. Experimental results and analysis

The influence of related factors on the atomization performance of the nozzle was experimented with the

orthogonal design scheme in Table 1. The results are shown in Table 2. Fig. 3 shows the distribution of droplet size under 25 operating conditions, in which the red curve represents the cumulative percentage of the droplet size, and the blue column represents the volumetric frequency of the droplet size.

Table 2 Orthogonal experiment results.

NO.	Influence factor			Experiment result		
	$p_{\text{air}}/\text{MPa}$	p_{L}/MPa	d/mm	$Q_{\text{L}}/(\text{L}\cdot\text{min}^{-1})$	$Q_{\text{air}}/(\text{L}\cdot\text{min}^{-1})$	SMD/ μm
1	0.2	0.2	0.8	0.83	31	52.28
2	0.2	0.3	1.0	1.50	23	68.45
3	0.2	0.4	1.2	2.33	32	78.23
4	0.2	0.5	1.5	3.00	33	88.24
5	0.2	0.6	1.8	4.67	17	95.80
6	0.3	0.2	1.0	1.00	40	43.92
7	0.3	0.3	1.2	2.00	48	66.04
8	0.3	0.4	1.5	2.50	43	82.46
9	0.3	0.5	1.8	3.33	27	87.35
10	0.3	0.6	0.8	1.17	43	61.89
11	0.4	0.2	1.2	1.33	76	38.52
12	0.4	0.3	1.5	1.83	66	50.80
13	0.4	0.4	1.8	3.00	43	77.08
14	0.4	0.5	0.8	1.17	56	48.19
15	0.4	0.6	1.0	1.50	45	69.79
16	0.5	0.2	1.5	1.17	98	39.55
17	0.5	0.3	1.8	1.33	80	57.31
18	0.5	0.4	0.8	0.83	73	36.60
19	0.5	0.5	1.0	1.17	66	49.94
20	0.5	0.6	1.2	1.83	78	63.96
21	0.6	0.2	1.8	0.50	157	40.48
22	0.6	0.3	0.8	0.50	91	20.21
23	0.6	0.4	1.0	1.17	94	39.57
24	0.6	0.5	1.2	1.83	96	50.89
25	0.6	0.6	1.5	2.17	88	70.08

Fig. 3. The droplet size distribution under 25 operating conditions.

The orthogonal experimental results in Table 2 and Fig. 3 show wide distribution of the nozzle's atomization characteristic parameters, which can basically meet the requirements of investigation and analysis. The wide distribution of the experimental results indicated that the level of factors was not limited to local areas, but can accurately reflect the overall situation of the factors, indicating that the orthogonal experiment design scheme was reasonable and effective (Dong et al 2012; Lin et al., 2016). At industrial production sites, according to the requirements on the nozzle atomization parameters, a parameter combination that approximated the requirements of the conditions can be selected from the orthogonal experimental results in Table 2.

Fig. 4. The relationship between SMD and three factors: (a) p_{air} ; (2) p_L ; and (3) d .

By comprehensively averaging the SMD data in Table 2, the influencing significance of the various factors on SMD can be obtained through range analysis. Fig. 4 shows the average value and range of SMD. From Fig. 4, among the three influencing factors for the droplet size, the range of air pressure is the largest. The influencing significance of

various factors can be ranked as $R_{air} > R_L > R_d$. From the overall trend of SMD, SMD was negatively correlated with air pressure, positively correlated with water pressure and outlet diameter.

The experimental results on the flow rate showed that at a higher air pressure, the air flow rate of the nozzle was lower and the water flow rate was greater. As the air flow rate increased, the velocity of the gas-liquid two-phase flow at the outlet increased, the intensity of the ultrasonic waves increased, and the generated effect on the surface of the droplets became more significant. As a result, the oscillation frequency of the bubbles was larger, and the particle size of droplets decreases. The increase of the outlet diameter led to a continuous increase in water flow rate. In contrast, at a relatively stable air flow rate, the atomization energy was reduced for a unit mass of water, which affected the effect of the primary and secondary atomization of the liquid. Consequently, the droplet got larger and larger. The increase in water pressure led to a greater water flow rate and a lower air flow rate. As a result, the air-to-liquid flow ratio to continuously decrease, as shown in Fig. 5. At a lower air-liquid flow ratio of nozzle, the required atomization energy for a unit mass of droplets was decreased, thus both the primary atomization and the secondary atomization effects became weaker, and the increase of droplet size.

Fig. 4. The impact of water pressure on the air-liquid flow ratio and the nozzle flow.

4. Establishment and verification of mathematical model

In the previous section, the nozzle atomization parameters under 25 operating conditions were analyzed with the orthogonal experiment design. However, it is difficult to study the relationship between the nozzle SMD and the influencing factors using the traditional methods, because the influencing factors are diverse and complicated. Multivariate nonlinear analysis methods can greatly approximate measured data, thus constructing mathematical models that can realistically reveal the relationship between input and output variables. In this study, a multivariate nonlinear analysis method was adopted to establish the prediction model for the nozzle SMD.

4.1. Establishment of mathematical model

Multivariate nonlinear regression should know the mathematical model form, and then fit the model coefficient. In order to establish the mathematical model of nozzle SMD prediction, several single-factor fitting formula were firstly obtained, then the best fitting formula were determined by variance analysis and regression analysis, and then the single-factor fitting formula were synthesized into multivariate nonlinear mathematical model. According to the change law of air pressure and SMD, eight functions, such as linear function, logarithmic function and S-shape function, were used in SPSS software for fitting. The statistical results of each function fitting were shown in Table 3. R^2 measures the goodness of fit of the model, and the closer R^2 is to 1, the better. F is a statistic to test the significance of the formula, which is the ratio of the mean regression sum of squares to the mean residual sum of squares. The larger F is, the better the fit is. The closer the regression significance is to 0, the better the fitting is (Yang et al., 2018).

Table 3 Fitting results of air pressure and SMD.

Function	R^2	ANOVA				Parameters estimated by function			
		F	Degree of freedom 1	Degree of freedom 2	Regression significance	Constant	Factor 1	Factor 2	Factor 3
Linear	0.984	181.650	1	3	0.001	92.512	-83.500		
Logarithmic	0.987	219.342	1	3	0.001	29.037	-30.480		
S-shape	0.903	27.794	1	3	0.013	3.593	0.161		
Exponential	0.997	439.050	1	3	0.000	102.187	-1.419		
Inverse function	0.936	44.014	1	3	0.007	31.055	9.675		
Power function	0.973	108.389	1	3	0.003	34.950	-0.512		
Quadratic	0.994	172.564	2	2	0.006	102.712	-141.786	72.857	
Cubic	0.998	202.028	3	1	0.052	80.032	58.914	-467.143	450.000

As can be seen from Table 3, among the 8 functions, R^2 of cubic function, exponential function and quadratic function are all greater than 0.99, indicating that their goodness of fit is better. The regression significance of the function indicates that the exponential function is the best fit, with the maximum F and the minimum regression significance. Meanwhile, according to the significance of regression coefficients in Table 4, the significance of quadratic function and cubic function is far greater than that of exponential function. From the above analysis, it is concluded that the variation law of air pressure and SMD is in the form of exponential function.

Table 4 Significance of regression coefficients t of the Function.

Function	Fitting formula	Significance of regression coefficient			
		Constant	Coefficient 1	Coefficient 2	Coefficient 3
Linear	$y = 92.512 - 83.5x$	0.000	0.001		
Logarithmic	$y = 29.037 - 30.48 \ln(x)$	0.001	0.001		
S-shape	$y = e^{3.593 + 0.161/x}$	0.000	0.013		
Exponential	$y = 102.187e^{-1.419x}$	0.000	0.000		
Inverse function	$y = 31.055 + 9.675 / x$	0.007	0.007		
Power function	$y = 34.95x^{-0.512}$	0.000	0.001		
Quadratic	$y = 102.712 - 141.786x + 72.857x^2$	0.003	0.044	0.197	
Cubic	$y = 80.032 + 58.914x - 467.143x^2 + 450x^3$	0.118	0.727	0.403	0.359

For the change relationship between other factors and SMD, the same analysis method as above was used to obtain the optimal fitting formula, and the optimal fitting formula between the three factors and SMD was summarized in Table 5.

Table 5 Fitting formula between single factor and SMD.

Factor	Function expression	Fitting formula	R^2
p_{air}	$y_1 = b_1 e^{b_2 x_1}$	$y_1 = 102.187e^{-1.419x_1}$	0.993
p_L	$y_2 = b_1 + b_2 \ln(x_2)$	$y_2 = 84.978 + 26.216 \ln(x_2)$	0.984
d	$y_3 = b_1 + b_2 / x_3$	$y_3 = 93.65 - 40.341/x_3$	0.996

According to the fitting formulas between single factor and SMD in Table 5, a multivariate nonlinear regression mathematical model is established (Li et al., 2016; Xie et al., 2010):

$$y = b_1 + b_2 e^{-1.419x_1} + b_3 \ln(x_2) + b_4 / x_3 \quad (1)$$

Where, y represents SMD, μm ; x_1 represents air pressure (p_{air}), MPa; x_2 represents water pressure (p_L), MPa; x_3 represents outlet diameter (d), mm; b_k represents regression coefficient, $k=1\sim4$. According to the measured 25 groups of experimental data, the multivariate nonlinear regression was selected in SPSS software and the model (1) was input to fit the model coefficient, and the multivariate nonlinear regression mathematical model was as follows:

$$y = 54.799 + 106.504 e^{-1.419x_1} + 25.198 \ln(x_2) - 38.033 / x_3 \quad (2)$$

Multiple nonlinear regression equation (2) R^2 is equal to 0.962, and the goodness of fit of the regression model is good. In order to further improve the goodness of fit and the accuracy of predicted values of the regression model, considering the interaction between various factors, the correction terms were added on the basis of the original model. The modified multivariate nonlinear regression mathematical model is:

$$y = b_1 + b_2 e^{-1.419x_1} + b_3 \ln(x_2) + b_4 / x_3 + b_5 x_1 x_2 + b_6 x_1 x_3 + b_7 x_2 x_3 \quad (3)$$

According to the 25 groups of experimental data in Table 2, the multivariate nonlinear regression was selected in SPSS software and the prediction model of equation (3) was input. The revised multivariate nonlinear regression mathematical model was obtained as follows:

$$y = -14.465 + 172.912 e^{-1.419x_1} + 20.03 \ln(x_2) - 30.721 / x_3 + 68.262 x_1 x_2 + 22.905 x_1 x_3 - 5.414 x_2 x_3 \quad (4)$$

The modified prediction model R^2 is equal to 0.970, and the goodness of fit of multiple nonlinear regression is improved. The nozzle SMD can be calculated according to equation (4).

4.2 Verification of mathematical model

The model was used to calculate the SMD under the 25 experimental conditions to verify the accuracy of the prediction model. Then, we compared the calculation results with the orthogonal experimental data, as shown in Fig. 6. Fig. 6 shows that the calculated value of SMD from the prediction model was basically consistent with the orthogonal experimental results, and the relative error averaged only 4.39%.

Fig. 6. Comparison between predicted values and orthogonal experimental values results of SMD.

In order to further verify the validity of the established prediction model, a nozzle was selected to carry out the experiment, and the differences between the predicted SMD values of the nozzle and the experimental values were compared under different air pressure and water pressure. Fig. 7 shows the change curve of the predicted SMD value

and the experimental value of the nozzle with d equal to 2.0 mm. It can be seen from the figure that the predicted value has a consistent change trend with the experimental value, indicating that the model can qualitatively reflect the change rule of droplet particle size with the operating parameters. At the same time, the average relative error between the predicted value and the experimental value is only 4.89%. Considering the influence of the experimental environment on the spray field and the complex environment of the actual engineering site, there are many environmental factors that affect the particle size of drops, so it can be considered that the model error is within the acceptable range. Therefore, it can be seen that the prediction model of nozzle SMD established in this study has high accuracy and can be used for theoretical prediction calculation of nozzle SMD.

Fig. 7. The predicted value and experimental value of nozzle SMD.

The droplet size is an important parameter affecting spray dust reduction. In practical application, the influencing factors of droplet size include air pressure, water pressure and outlet diameter. When the three factors are known, the nozzle SMD can be predicted according to the prediction model. At the same time, in order to obtain the appropriate droplet size, the three factors can be changed according to the prediction model. The nozzle is widely used. Due to the complexity and variability of the environment in practical application, arbitrary changes of the three factors are limited. Therefore, in order to obtain the appropriate droplet size, other factors can be adjusted through the prediction model under the condition of one factor limitation, as shown in Fig. 8. It can be seen that the prediction model can be used to determine the size of the three factors in the engineering application of spray dust reduction, which can provide guidance for the practical application of the nozzle. The variation law of the three factors and SMD plays an important role in the engineering application of the nozzle. The relationship between the three factors and SMD is established through the prediction model.

Fig. 8. The relationship between nozzle SMD and various factors.

5. Conclusions

In this study, by applying the orthogonal design method, the atomization parameters of a hydrodynamic ultrasonic atomization nozzle were obtained under 25 operating conditions using a Malvern real-time high-speed spray particle size analyzer, an intelligent electromagnetic flow meter and an air mass flow meter. Then the relationship between the atomization parameters and the influencing factors was analyzed by the means of average and range. The atomization parameters in the analysis included air flow rate, water flow rate, and droplet size, while the influencing factors included air pressure, water pressure, and nozzle outlet diameter. On this basis, a multivariable nonlinear regression method was used to construct a model for predicting the SMD of this type of nozzles. The predicted values of the SMD by the established mathematical model basically agreed with the experimental results, and the average relative error was only about 5%. Thus the developed model for both the SMD can be used for theoretical prediction for the nozzle.

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Conflict of interest

The authors declare no conflict of interest.

References

- Rasmussen, P. E., Levesque, C., Chénier, M., Gardner, H.D., Otazo, H.J., Petrovic, S., 2013. Canadian House Dust Study: Population-based concentrations, loads and loading rates of arsenic, cadmium, chromium, copper, nickel, lead, and zinc inside urban homes. *Science of the Total Environment* 443: 520-529.
- Tatyana, G. K., Olga, V. R., Irina, V. M., Artyukov, E.V., 2019. Health risk assessment of metal(loid)s exposure via indoor dust from urban area in Chelyabinsk, Russia. *International Journal of GEOMATE* 16: 1-7.
- Chen, L.J., Li, P.C., Liu, G.M., Cheng, W.M., Liu, Z.X., 2018. Development of cement dust suppression technology during shotcrete in mine of China-A review. *Journal of Loss Prevention in the Process Industries* 55: 232-242.
- Han, W.B., Zhou, G., Gao, D.H., Zhang, Z.X., Wei, Z.Y., Wang, H.T., Yang, H.Q., 2020a. Experimental analysis of the pore structure and fractal characteristics of different metamorphic coal based on mercury intrusion-nitrogen adsorption porosimetry. *Powder Technology* 362: 386-398.
- Kumia, J.C., Sasmito, A.P., Mujumdar, A.S., 2014. Dust dispersion and management in underground mining faces. *International Journal of Mining Science and Technology* 24: 39-44.
- Li, Y.J., Wang, P.F., Liu, R.H., Jiang, Y.D., Han, H., 2020. Determination of the optimal axial-to-radial flow ratio of the wall-mounted swirling ventilation in fully mechanized excavation face. *Powder Technology* 360: 890-910.
- Inoka, E.P., Marcia, L.H., Michael, L.S., 2019. Examination of classified rock dust (treated and untreated) performance in a 20-L explosion chamber. *Journal of Loss Prevention in the Process Industries* 62, 103943.
- Ji, Y.L., Reng, T., Peter, W., Wan, Z.J., Ma, Z.Y., Wang, Z.M., 2016. A comparative study of dust control practices in Chinese and Australian longwall coal mines. *International Journal of Mining Science and Technology* 26 (2): 199-208.
- Han, H., Wang, P.F., Li, Y.J., Liu, R.H., Tian, C., 2020b. Effect of water supply pressure on atomization characteristics and dust-reduction efficiency of internal mixing air atomizing nozzle. *Advanced Powder Technology* 31: 252-268.
- Liu, Z.Q., Zhou, G., Song, S.Z., Meng, Q.Z., Zhang, Q., Liu, W., 2020. Synthesis and characteristic analysis of coal dust explosion suppressant based on surface modification of ammonium dihydrogen phosphate with methyl hydrogen-containing silicone oil. *Journal of Loss Prevention in the Process Industries* 64, 104059.
- Wang, P.F., Li, Y.J., Liu, R.H., Shi, Y.J., 2019a. Effect of forced-to-exhaust ratio of air volume on dust control of wall-attached swirling ventilation for mechanized excavation face. *Tunnelling and Underground Space Technology* 90: 194-207.

- Xiu, Z.H., Nie, W., Chen, D.W., Yan, J.Y., Cai, P., Liu, Q., Wei, C.H., 2019. Numerical simulation study on the coupling mechanism of composite-source airflow–dust field in a fully mechanized caving face. *Powder Technology* 356: 443-457.
- Cheng, W.M., Ma, Y.Y., Yang, J.L., Sun, B., 2016. Effect of atomization parameters of dust removal nozzles on the de-dusting results for different dust sources. *International Journal of Mining Science and Technology* 26 (6): 1025-1032.
- Hu, S.Y., Liao, Q., Feng, G.R., Huang, Y.S., Shao, H., Gao, Y., Hu, F., 2020. Influences of ventilation velocity on dust dispersion in coal roadways. *Powder Technology* 360: 683-694.
- Zhou, W.D., Wang, H.T., Wang, D.M., Zhang, K., Du, Y.H., Yang, H.S., 2020. The effect of geometries and cutting parameters of conical pick on the characteristics of dust generation: Experimental investigation and theoretical exploration. *Fuel Processing Technology* 198: 106243.
- Cheng, W.M., Zhou, G., Chen, L.J., Wang, G., Nie, W., Zhang, Q.T., 2020. Research progress and prospect of dust control theory and technology in China's coal mines in the past 20 years. *Coal Science and Technology* 48(02): 1-20.
- Xu, G., Chen, Y. P., Eksteen, J., Xu, J. L., 2018. Surfactant-aided coal dust suppression: A review of evaluation methods and influencing factors. *Science of The Total Environment* 639: 1060-1076.
- Han, W.B., Zhou, G., Zhang, Q.T., Pan, H.W., Liu, D., 2020c. Experimental study on modification of physicochemical characteristics of acidified coal by surfactants and ionic liquids. *Fuel* 266, 116966.
- Hu, S.Y., Huang, Y.S., Feng, G.R., Shao, H., Liao, Q., Gao, Y., Hu, F., 2019. Investigation on the design of atomization device for coal dust suppression in underground roadways. *Process Safety and Environmental Protection* 129: 230-237.
- Bao, Q., Nie, W., Liu, C.Q., Zhang, H.H., Zhan, Wang, H.K., Jin, H., Yan, J.Y., Liu, Q., 2020. The preparation of a novel hydrogel based on crosslinked polymers for suppressing coal dusts. *Journal of Cleaner Production* 249, 119343.
- Liu, C.Q., Nie, W., Bao, Q., Liu, Q., Wei, C.H., Hua, Y., 2018. The effects of the pressure outlet's position on the diffusion and pollution of dust in tunnel using a shield tunneling machine. *Energy & Buildings* 176: 232-245.
- Wang, H.T., Wei, X.B., Du, Y.H., Wang, D.M., 2019b. Experimental investigation on the dilatational interfacial rheology of dust-suppressing foam and its effect on foam performance. *Process Safety and Environmental Protection* 123: 351-357.
- Wang, H.T., Wei, X.B., Du, Y.H., Wang, D.M., 2019c. Effect of water-soluble polymers on the performance of dust-suppression foams: wettability, surface viscosity and stability. *Colloids and Surfaces A-Physicochemical and Engineering Aspects* 568: 92-98.
- Wang, P.F., Tan, X.H., Zhang, L.Y., Li, Y.J., Liu, R.H., 2019d. Influence of particle diameter on the wettability of coal dust and the dust suppression efficiency via spraying. *Process Safety and Environmental Protection* 132: 189-199.
- Zhou, Q., Qin, B.T., Wang, F., Wang, H.T., 2019b. Experimental investigation on the performance of a novel magnetized apparatus used to improve the dust wetting features of surfactant-magnetized water. *Powder Technology* 354:, 149-157.
- Dobre, M., Bolle, L., 2002. Practical design of ultrasonic spray devices: Experimental testing of several atomizer geometries. *Experimental Thermal and Fluid Science* 26: 205-211.
- Kudo, T., Sekiguchi, K., Sankoda, K., Namiki, N., Nii, S., 2017. Effect of ultrasonic frequency on size distribution of nanosized mist generated by ultrasonic atomization. *Ultrasonics Sonochemistry* 37: 16-22.
- Loomis, W. R., and Woods, A. L., 1927. The physical and biological effects of high frequency sound waves of great intensity. *Philosophical Magazine Letters* 4: 417-436.
- Lang, R.J., 1962. Ultrasonic atomization of liquid. *Journal of the Acoustical Society of America* 34. <https://doi.org/10.1121/1.1909020>.
- Sarohia, V., Back, L.H., 1979. Experimental investigation of flow and heating in a resonance tube. *Journal of Fluid Mechanics* 94: 649-672.
- Sobieraj, G.B., Szumowski, A.P., 1991. Experimental investigations of an underexpanded jet from a convergent nozzle impinging on a cavity. *Journal of Sound and Vibration* 149: 375-396.
- Hamed, A., Cincinnati, U.O., 2003. Numerical simulation and parametric study of Hartmann-Sprenger tube based powered device. *American Institute of Aeronautics and Astronautics* 35: 25-50.

- Narayanan, S., Bhawe, P., Srinivasan, K., Sundararajan, T., 2009. Spectra and directivity of a Hartmann whistle. *Journal of Sound and Vibration* 321: 875-892.
- Kim, K.D., Jin, D.H., Choi, Y.C., 2018. Numerical simulation on the generation of ultrasound and formation of water fog in the ultrasonic gas atomizer. *Ultrasonics*. <https://doi.org/10.1016/j.ultras.2018.11.002>
- Zhang, S.K., Wang, J.F., Ma, C.F., Shi, Y., 2007. Experimental study of atomization characteristic of fluid dynamic ultrasonic nozzle. *China Petroleum Machinery* 35: 1-3,7.
- Zhang, S.K., 2010, Research of atomization characteristics of ultrasonic heavy oil nozzle, *Industrial Furnace* 32: 5-8.
- Sun, X.X., 2004. Recent research advances of ultrasonic atomizer. *Industrial Furnace* 26, 19-23; 32.
- Zhang, X.Y., Wang, X.W., 2002. Experimental study and regressive analysis on ultrasonic dispersal property. *Industrial Safety and Environmental Protection* 28: 8-13.
- Zhang, J., Peng, Y.T., Lin, Q.Z., 2017. Simulation on internal flow field characteristic of ultrasonic atomizer based on CFD. *China Powder Science and Technology* 23: 20-23.
- Li, H.X., Liu, Q.Z., Liu, Y.P., Zhang, J.L., 2017. Numerical simulation on atomization characteristics of ultrasonic vibration nozzle based on CFD. *Chinese Journal of Vacuum Science and Technology* 37: 113-117.
- Li, H.X., Zhang, J.L., Lin, Y.P., Lin, Q.Z., 2018. Simulation research on cavitation flow characteristics of ultrasonic atomization nozzle for mine dust suppression. *Safety in Coal Mines* 49: 40-43.
- Gao, J.M., Ma, J.L., 2017. Design and test of low-frequency Hartmann atomization nozzle with stepped resonance tube. *Transactions of the Chinese Society of Agricultural Engineering* 33: 66-73.
- Wang, P.F., Zhang, K., Liu, R.H., 2019e. Influence of air supply pressure on atomization characteristics and dust-suppression efficiency of internal-mixing air-assisted atomizing nozzle. *Powder Technology* 355: 393-407.
- Wang, P.F., Shi, Y.J., Zhang, L.Y., Li, Y.J., 2019f. Effect of structural parameters on atomization characteristics and dust reduction performance of internal-mixing air-assisted atomizer nozzle. *Process Safety and Environmental Protection* 128: 316-328.
- Wang, P.F., Tian, C., Liu, R.H., Wang, J., 2019g. Mathematical model for multivariate nonlinear prediction of SMD of X-type swirl pressure nozzles. *Process Safety and Environmental Protection* 125: 228-237.
- Dong, J.Y., Yang, J.H., Yang, G.X., et al., 2012. Proportioning test of similar materials in model test based on orthogonal design. *Journal of China Coal Society*. 37: 44-49.
- Lin, H.F., Yan, Y.L., Li, S.G., et al., 2016. Experimental study on mechanical and permeability characteristics of similar materials based on orthogonal design for solid-gas coupling. *Journal of China Coal Society*. 41:, 672-679.
- Yang, J., Chang, J.X., Wang, Y.M., et al., 2018. Comprehensive drought characteristics analysis based on a nonlinear multivariate drought index. *Journal of Hydrology*. 557: 651-667.
- Li, S., Du, Y.J., 2016. Concrete strength prediction model based on multivariate nonlinear analysis. *Concrete*. 38: 44-46+55.
- Xie, S.C., Gao, G.J., 2010. Multivariate nonlinear regression analysis of energy absorption prediction for thin-wall structures. *Journal of Applied Basic and Engineering Sciences*. 18: 714-721.

Figures

Figure 1

The ultrasonic atomizing nozzles used in experiment.

Figure 2

The experimental platform.

Figure 3

The droplet size distribution under 25 operating conditions.

Figure 4

The relationship between SMD and three factors: (a) pair; (2) pL; and (3) d.

Figure 5

The impact of water pressure on the air-liquid flow ratio and the nozzle flow.

Figure 6

Comparison between predicted values and orthogonal experimental values results of SMD.

Figure 7

The predicted value and experimental value of nozzle SMD.

Figure 8

The relationship between nozzle SMD and various factors.