Optimal design of a pneumatic atomizer using response surface method to obtain more uniform coatings

Wentong Qiao¹, Lijuan Qian¹,², Chenlin Zhu¹ and Jingqi Liu¹

Abstract
Uneven coatings with overspray often occur to the target plate when using a pneumatic atomizer. This issue is mainly due to the high-level pressure in the plate center, which results from unreasonable design of the structure and operating parameters in atomizer. In this paper, an optimal design for these parameters was established by response surface method (RSM) and computational fluid dynamics (CFD) to produce more uniform coatings. The velocity data measured by a hot-wire anemometry experimentally verified the numerical model. Then, annular air hole diameter, horn flare angle, annular air pressure, and shaping air pressure were selected as design variables while the central pressure was chosen as objective function. The RSM with the central composite design (CCD) was employed to construct the regression equation that expresses the relationship between the central pressure and design parameters. Finally, the optimum combination of the parameters was carried out for reducing the central pressure, and the interaction effects between the parameters were also analyzed. The optimization results show that the central pressure is decreased by 44.6% and the performance of droplet size distribution is significantly improved. The experiment confirmed the effectiveness of the optimized atomizer to obtain well-distributed coatings.

Keywords
Pneumatic atomizer, optimal design, response surface method, spray coatings, pressure distribution, CFD

Introduction
Pneumatic atomizers are widely used for surface coatings and manufacturing of new materials with peculiar properties. They can provide better atomization characteristics, along with the ultrafine coatings that result in a remarkable improvement of protective and esthetic properties, especially in the painting industry.¹⁻³ In contrast to other types of spray painting, such as airless atomizers, and rotary bell atomizers, the gas flow field of the pneumatic atomizer exerts excessive pressure on the central region of the target plate, which will bring about overspray, painting liquid sagging, and lower transfer efficiency.⁴⁻⁷ As the key factor in the spray coating process, the homogenization of the pressure distribution on the plate directly affects the formation of the uniform coatings. However, local high-level pressure often occurs to the plate because of the

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unreasonable design of the geometrical structure and operating conditions in atomizer. Therefore, the liquid paint is easily concentrated in the plate center, which leads to uneven coatings with the over-spray happening from time to time.\textsuperscript{8–10} To solve this problem, a repeatable and comprehensive design for the pneumatic atomizer must be done, which means the interactions between the influential factors should be considered simultaneously.\textsuperscript{9}

Many experimental and numerical investigations on spray coatings using the pneumatic atomizer have been carried out in recent years,\textsuperscript{11–14} referring mainly to the influence of the geometrical structure and operating conditions. Fogliati et al.\textsuperscript{15} analyzed the mechanism of spray deposition by computational fluid dynamics (CFD) to predict paint droplet trajectories and film builds on the target plate though the secondary breakup of droplets was not considered. They investigated the influence of the rectangular target plate and its orientation on the paint film thickness. Further, some researchers focused on more complicated target plates, such as the inclined plane,\textsuperscript{16} concave stepped surface,\textsuperscript{13} and inner or outer cylindrical surface,\textsuperscript{17} to fit in unforeseeable working situations. In terms of the operating conditions, Ye and Pulli\textsuperscript{13} studied the effects of the atomizing and the shaping air flow rate on the droplet size distribution. Li et al.\textsuperscript{10} found that increasing the central pressure was beneficial to even coatings. Whereas an increment in horn flare angle would aggravate the uneven coatings due to the too high pressure in the plate center. They also pointed out that the greater the center pressure was, the easier it was to cause over-spray. Wang et al.\textsuperscript{8} proposed a double-nozzle atomizer and thought that uneven coatings with overspray easily happened when the distance between the two paint holes and the angle between the axes of the paint holes were both small. Conversely, the coating film shape became a concave that would slightly cause uneven coatings. In summary, many scholars devoted much to promoting the painting performance of the pneumatic atomizer from different individual aspects, and studies of other types of air atomizers on spray characteristics had been also performed.\textsuperscript{2,18–21} However, the interaction effects of the structure and operating parameters on the spray coating were rarely mentioned. Besides, lots of time and cost will be spent on the experiments and simulations for these issues due to insufficient samples for accuracy improvement. Therefore, only using experiment or simulation means to optimize the parameters of the atomizer can hardly improve the uniformity of spray coating as a whole. It is necessary to employ the optimization methodology to design the atomizer comprehensively.

Response surface methodology (RSM) is a multidisciplinary design optimization method that combines statistical mathematics and computer technology. This technique can be used to determine the relationship between various design parameters and the desired responses with the advantages of design cycle-shortening and experimental cost-saving.\textsuperscript{22–24} Some scholars have tried to apply this technique to the fields relevant to the optimization of spray coatings.\textsuperscript{25,26} For example, Müller and Kleinebudde\textsuperscript{27} especially conducted a complete 3\textsuperscript{2} factorial design of experiment (DOE) to correlate the atomization and pattern air pressure with the spray width using RSM. An optimal atomization air/pattern air ratio of atomizer for a good coating process has been found. In the research of Seyedin et al.,\textsuperscript{28} in order to optimize the coating mass of particles in a top-spray fluidized bed coating, they adopted RSM to conduct an experimental investigation. The effect of the fluidization air flow rate, atomization air flow rate, and liquid flow rate on the coating mass was determined by using DOE. Additionally, other scholars have optimized the structure of spraying equipment in this way, such as Wang et al.\textsuperscript{29} They combined the RSM technique and the non-dominated sorting genetic algorithm to perform a CFD-based multi-objective optimization design for the structural and operating parameters of the self-excited oscillation nozzle, aiming at improving the jet atomization quality.

To the authors’ knowledge, there are inadequate investigations concerning the optimization of design parameters of a pneumatic atomizer with multi-hole structure, which plays a vital role in improving spray coating quality. Therefore, in this paper, based on RSM technique, an optimal design for the structure and operating parameters in atomizer was developed with the help of the commercial CFD solver, aiming at reducing the local high pressure on the target plate and producing well-distributed coatings. This study effectively optimizes the pneumatic atomizer and provides reliable technical guidance for the design of the nozzle in the future.

This paper is organized as follows. In “Numerical setup” section, the atomizer geometry, the mathematical model and the numerical methods are explained. A hot-wire anemometry measuring system is built to measure the gas velocity for proving the numerical model is reliable. “Application of response surface method” section shows the application process of the RSM for optimizing the atomizer. “Results and discussion” section includes the statistical evaluation of the regression equation and the analysis of the response surface graphs. The central pressure and the droplet size distributions before and after optimization are discussed. “Confirmation experiments of spraying coatings” section conducts the experiment to confirm that the RSM-based optimal design of the atomizer is feasible. “Conclusions” section summarizes the conclusions.
Table 1. Structure parameters of pneumatic atomizer.

| Structure parameters          | Dimension |
|------------------------------|-----------|
| Paint hole diameter          | 0.8 mm    |
| Annular air hole diameter \(d\) | 2.8 mm    |
| Annular air hole inner diameter \(d_i\) | 1.8 mm    |
| Auxiliary air hole diameter  | 0.5, 0.7 mm |
| Shaping air hole diameter    | 1.3 mm    |
| Horn flare angle \(\alpha\)   | 25°       |

**Numerical setup**

**Pneumatic atomizer geometry**

The structure of the pneumatic atomizer consists of paint hole, annular air hole, auxiliary air holes, and shaping air holes as shown in Figure 1, where \(d\) is the annular air hole diameter, \(d_i\) is the annular air hole inner diameter, and \(\alpha\) is the horn flare angle. The atomizer can be assembled to spray gun or robotic arm for spraying painting. Table 1 shows the main structural parameters of the atomizer. As shown in Figure 2, with the help of the high-speed gas from the multi-holes, the spray flow field shaped as an elliptical cone is formed between the nozzle and the target plate, completing the primary and secondary atomization of the painting liquid. Then, under the pressure of the airflow acting on the plate, the tiny droplets cover and deposit on the plate to form an elliptic coating film. As one of the main reasons, the high-level pressure in the plate center will result in uneven coatings with overspray, which is harmful to the coating quality.9,10

**Mathematical model**

**Gas phase.** The gas phase in the spray flow field is governed by the fundamental conservation law, namely the continuity and momentum equations. The prediction of the gas flow field was obtained by solving the time-averaged Navier–Stokes equations and combining with the appropriate closure model for turbulence. The most commonly used model is \(k - \varepsilon\) model, proposed by Launder and Spalding.30 Compared with the standard \(k - \varepsilon\) model, the realizable \(k - \varepsilon\) model can more accurately predict the divergence ratio of the cylindrical jet, and it performs well for complex flows such as rotating flow, boundary layer flow with strong adverse pressure gradient, flow separation, and secondary flow. The gas flow near the multi-holes in pneumatic atomizer is under a supersonic condition with the complexity of movement mechanism. Therefore, the realizable \(k - \varepsilon\) turbulence model was adopted to describe the turbulent gas phase.4

**Discrete phase.** The spray flow field can be seen as gas-liquid two-phase flow that is described by the discrete particle model (DPM). DPM is a multiphase flow model based on the Eulerian–Lagrangian method, which is used to simulate the movement of droplet particles in the gas phase. The gas governing equation is solved as a continuous phase in the Eulerian coordinate system, and the liquid droplet particles are regarded as a discrete phase in the Lagrangian coordinate system.51 The motion equation of a particle is expressed as:

\[
\frac{du_p}{dt} = \frac{u_g - u_p}{\tau_f} + \frac{g(\rho_p - \rho_g)}{\rho_p} + \Delta
\]  

where \(u_p\) and \(u_g\) are, respectively, the velocity vectors of liquid droplet particles and gas phase, \(\rho_p\) is the density of liquid droplet particles, \(\rho_g\) is the density of gas phase, \(\Delta\) is the other acceleration term for the particle mass, \(\tau_f\) is the relaxation time of discrete phase, and \(g\) is the gravitational acceleration.

The Taylor analogy breakup (TAB) model, used to analyze the droplet oscillation and the secondary breakup,32,33 is shown as:

\[
F - kx - d\frac{dx}{dt} = \frac{m}{d} \frac{d^2x}{dt^2}
\]  

where \(x\) is the displacement of the droplet equator from its spherical position. The coefficients of this equation are derived from Taylor analogy34:

\[
\frac{F}{m} = C_f \frac{\rho_p u^2}{\rho_g}
\]

\[
\frac{k}{m} = C_k \frac{\sigma}{\rho_p r^3}
\]

\[
\frac{d}{m} = C_d \frac{\mu_p}{\rho_g r^2}
\]

where \(r\) is the initial droplet radius, \(u\) is the relative velocity of the droplet, \(\sigma\) is the droplet surface tension, \(\mu_p\) is the droplet viscosity, \(C_f = 1/3\), \(C_k = 8\), and \(C_d = 5\).

**Coating film.** The Eulerian wall film (EWF) model was employed to calculate the distribution of the coating film thickness on the target plate16,35 When the liquid droplets in the spray flow field impinge on the plate and deposit to form a coating film, the mass and momentum of the liquid phase are removed from the two-phase flow and added as source terms to the mass and momentum conservation equations of the liquid film, respectively. Therefore, the thickness of the coating film can be calculated through the mass and momentum conservation equations of the liquid film17,36

The mass conservation equation of the film is

\[
\frac{\partial h}{\partial t} + \nabla \cdot (h \mathbf{v}_l) = \frac{\bar{m}_g}{\rho_l}
\]  

where \(\rho_l\) is the density of liquid two-phase flow that is described by the discrete model, the appropriate closure model for turbulence. The most commonly used model is \(k - \varepsilon\) model, proposed by Launder and Spalding.30 Compared with the standard \(k - \varepsilon\) model, the realizable \(k - \varepsilon\) model can more accurately predict the divergence ratio of the cylindrical jet, and it performs well for complex flows such as rotating flow, boundary layer flow with strong adverse pressure gradient, flow separation, and secondary flow.
where $h$ is the height of liquid film, $\nabla_s$ is the surface gradient operator, $V_l$ is the mean film velocity, $\rho_l$ is the density of liquid film, and $\dot{m}_s$ is the mass source per unit area due to the impingement of droplets on the plate, which is given by:

$$\dot{m}_s = \alpha_d \rho_l V_{dn} A \tag{7}$$

where $\alpha_d$ is the volume fraction of liquid phase, $V_{dn}$ is the liquid velocity normal to the wall surface, and $A$ is the wall surface area.

The momentum conservation equation of the film is

$$\frac{\partial h V_l}{\partial t} + \nabla_s \cdot (h V_l V_l) = -h \nabla_s P_L \rho_l + g_s h + \frac{3}{2} \tau_{sl} - \frac{3v_l}{h} V_l + \frac{\dot{q}_s}{\rho_l} \tag{8}$$

The terms on the left represent the transient and convection effects, respectively. On the right hand, the first term involves the effects of gas-flow pressure, the gravity component normal to the wall surface, and the surface tension; the second term represents the effect of gravity in the direction parallel to the film; the third term is the viscous shear force at the gas-film interface; the fourth term represents the viscous force in the film, where $v_l$ is the kinematic viscosity of liquid; and the last term is the effect of the momentum source $\dot{q}_s$ for the wall film, in which $\dot{q}_s$ is given by:

$$\dot{q}_s = \dot{m}_s V_d \tag{9}$$

where $V_d$ is the velocity vector of liquid phase.

**Computational domain and numerical methods**

As shown in Figure 3, a cuboid block of $400 \text{ mm} \times 200 \text{ mm} \times 200 \text{ mm}$ was used as the computational domain. The atomizer is located in the center of plane ABCD. The distance from the atomizer to the target plate EFGH is $194 \text{ mm}$. As shown in Figure 4, unstructured meshes were chosen to discretize the three-dimensional computational domain, which could better fit the complex geometry of the atomizer. Local mesh refinements around the nozzle axis, elliptical spray cone, and the target surface were carried out. Sparser meshes were used in the region far away from the nozzle. As such, it can improve the calculation accuracy and reduce the consumption of computing resources.
The pressure-based solver and the semi-implicit method for pressure linked equations (SIMPLE) algorithm were employed in ANSYS Fluent. The turbulent kinetic energy and turbulent dissipation rate were both set as first-order upwind, and the other variables used second-order upwind. Pressure-inlet boundary conditions were set at annular air hole, auxiliary air holes, and shaping air holes. The target plate EFGH and the nozzle surface were set as no-slip wall boundary conditions. The other boundaries (planes ABFE, CDHG, ADHE, BCGF, and ABCD) were set as pressure-outlet conditions. The pressure-inlet boundaries for the atomizer holes were set the same as the initial operating parameters in the laboratory, which was shown in Table 2. The outlet pressure was set to 1 atm.

In previous studies,\textsuperscript{10,16} the initial condition of discrete phase in the spraying simulation was determined like this: the velocity and size distribution of droplets were measured by experiments that are expensive and time-consuming; then, the discrete phase was added at the inlet of paint hole to simulate the primary atomization when the liquid was assumed to be totally atomized. After that, the TAB model was used to predict the secondary breakup and the child droplets’ diameters. According to references\textsuperscript{8,10} after the computational results of gas phase tend to convergence, 120 non-Newtonian liquid particles at the paint hole were injected into the gas flow field. These particles have a diameter of 65 $\mu$m with Rosin–Rammler distribution and an initial velocity of 10 m/s (i.e. flow rate of 300 mL/min for the paint hole). The important properties of the materials used here were presented in Table 3. Moreover, the formation of the liquid film was simulated by EWF model when droplets impinge on the plate. The spraying time was 0.4 s and as such this numerical method can simulate the spray coating process.

According to the initial simulation works, it was found that a grid system with about 7–16 million cells can take into account both higher accuracy and computational cost. Specifically, grid systems with 7.4, 9.7, 13.2, and 15.8 million cells were created to conduct the grid independence test, as shown in Figure 5. The effects of four different grid systems on the gas velocity and pressure distribution along Z-axis were both analyzed. When the number of cells is more than 13.2 million, the velocity and pressure curves remain basically unchanged, which means the calculated results are convergent and independent of the number of cells.

### Table 2. Operating parameters of pneumatic atomizer.

| Operating parameters | Condition       |
|----------------------|-----------------|
| Annular air pressure $P_1$ | 250 kPa         |
| Auxiliary air pressure | 250 kPa         |
| Shaping air pressure $P_2$ | 120 kPa         |
| Liquid flow rate      | 300 mL/min      |

### Table 3. Properties of the paint and air.

| Materials          | Paint liquid | Air         |
|--------------------|--------------|-------------|
| Density (kg/m$^3$) | 1200         | 1.185       |
| Surface tension (mN/m) | 71.9        | —           |
| Viscosity (Pa s)   | 0.065        | $1.83 \times 10^{-5}$ |
| Temperature ($^\circ$C) | 25 $\pm$ 2   | 25 $\pm$ 2  |
Considering the computational time and cost, the grids with 13.2 million cells were adopted for the simulation.

**Experimental verification for spray flow field**

*Simulation results of the gas flow.* Simulation contours for velocity and pressure distribution of the gas flow are presented in Figure 6. Gas velocity distributions on the planes \(YZ\) and \(ZX\) (Figure 6(a) and (b)) show that the high-speed gas sprays out from the multi-holes and converges with each other. Then, the gas-flow spreads to the target plate EFGH in a flat elliptical cone shape. Finally, the gas flows out along the plate and forms an oval uneven pressure area on the plate (Figure 6(c)) with the highest pressure of 307.95 Pa, which will intensify the uneven coatings in the spray coating process.

*Experimental setup and verification.* As shown in Figure 7, to validate the reliability of the numerical model, a hot-wire anemometry measuring system, mainly composed of air source system, hot-wire anemometry (Dantec Dynamics A/S, Copenhagen, Denmark), and traverse system, was set up to obtain the velocity data of gas flow field. The gas source was provided by an air pump (FB-420/7, Shanghai Jiebao Compressor Manufacturing Co., Ltd., Shanghai, China). The airflow pressure was measured by the piezometer. The temperature of laboratory environment was kept at 25°C. The experimental operating conditions were conducted the same with the numerical simulation as shown in Table 2. Before measurement, the velocity calibration with the range of 0–100 m/s was conducted. Then, the velocity data acquisition was accomplished by the hot-wire probe. Moreover, the traverse coordinate system, controlled by a computer automatically, was used to move the probe in the space. The areas that need to be measured include the planes \(ZX\) and \(YZ\) (shown in Figure 3).

Figure 8 shows the quantitative comparisons of the experimental and calculated gas velocity evolution along the \(X\)-axis and \(Z\)-axis (in the plane \(ZX\)), respectively. With increasing the distance \(L\) between the measuring cross-section and the nozzle, the velocity curve tends to be flat progressively (Figure 8(a)). The gas velocity decays gradually downstream the nozzle due to the entrainment effects (Figure 8(b)). When close to the target surface \((L = 200 \text{ mm})\), the measured values are slightly larger than the calculated values. This is because there is no target plate installed in front of the atomizer in the experiment to facilitate the movement of the probe in space when measuring the velocity. The calculated results generally correspond with the experimental data, which indicates that the numerical model established above can be employed for the subsequent optimization study.

**Application of response surface method**

**Crucial design parameters**

The pressure distribution on the target plate is affected by the structure and operating parameters of the pneumatic atomizer that are shown in Tables 1 and 2. The size of annular air hole influences the flow rate of the spray gas, which is the main reason for local excessive pressure on the plate. The horn flare angle will influence the spatial distribution of the spray flow field and the pressure distribution on the plate.\(^{10,13}\) Besides, the annular and shaping air pressure determine the liquid break-up process and the atomization performance. The ovality of painting area is related to shaping air pressure. If the annular air/shaping air ratio is too low, a dumbbell pattern can be formed.\(^{27}\) Therefore, these
crucial factors including annular air hole diameter $d$, horn flare angle $\alpha$, annular air pressure $P_1$, and shaping air pressure $P_2$ were selected as the design variables to be optimized. On account of the existing atomizer and its working conditions, the ranges and three levels of each design variable were determined through the references $^4,^{13,16}$ and our previous work $^10$, as arranged in Table 4.

Figure 6. Simulation results of gas flow: (a) velocity contour on plane YZ, (b) velocity contour on plane ZX, and (c) pressure contour on the plate EFGH.

Figure 7. Hot-wire anemometry measuring system: (a) schematic diagram and (b) experimental setup.
Objective function

Since the high-level pressure occurred to the plate center is the incentive of uneven coatings, the optimization of coating quality can be converted into the homogenization of the pressure distribution. As shown in Figure 9, the pressure region with a value greater than 90 Pa (colored as red) considered here will result in uneven coatings on the plate. The area-weighted average is more reasonable than the mass-weighted average in the uneven distribution.29 Hence, the central pressure $P_c$, defined as the area-weighted average of the pressure in the region whose pressure value is more than 90 Pa, was chosen as the evaluation index for pressure distribution, namely the objective function. The central pressure $P_c$ is expressed as:

$$ P_c = \frac{1}{A} \int P \, dA = \frac{1}{A} \sum_{i=1}^{n} P_i |A_i| $$

where $A$ is the total area of the grids in selected regions, $P$ is the pressure, $P_i$ is the pressure of each grid, $A_i$ is the area of each grid, and $n$ is the number of the grids. In this way, the value of central pressure $P_c$ of the original atomizer is calculated as 170.04 Pa.

Central composite experiment design

The objective is to find a mathematical regression equation that can approximately model the objective function (the central pressure $P_c$) and the design variables by employing the design of experiment (DOE). DOE methods mainly contain full factorial, fractional factorial, Box-Behnken design, and central composite design (CCD). The CCD consists of factorial points, axial points, and center points, and it is widely used to fit

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Table 4. The design parameters and their levels.

| Factors                        | Codes | Levels |
|-------------------------------|-------|--------|
| Annular air hole diameter $d$ (mm) | A     | 2.3    | 2.8    | 3.3    |
| Horn flare angle $\alpha$ (°)  | B     | 20     | 29     | 38     |
| Annular air pressure $P_1$ (kPa) | C     | 140    | 240    | 340    |
| Shaping air pressure $P_2$ (kPa) | D     | 100    | 170    | 240    |

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Figure 8. Comparison of experimental and calculated gas velocity evolution: (a) gas velocity along the X-axis ($L$ is the distance between the measuring cross-section and the nozzle) and (b) gas velocity along the Z-axis.

Figure 9. Pressure area with the value greater than 90 Pa.
second-order polynomial models. In this study, the face centered central composite design (FCCCD) was used as the experiment plan, in which the axial points are at the center of each face of the factorial. Thirty-group schemes were determined as shown in Table 5. The response of each scheme was obtained through numerical simulation.

Regression equation

The relationship between the central pressure \( P_c \) and the design variables can be expressed as a regression equation via the statistical technique of regression analysis. The general formation for the polynomial regression model is expressed as:

\[
Y = \hat{y}(x) + \varepsilon
\]

where \( Y \) is the accurate response, \( \hat{y}(x) \) is the response surface approximation model, \( x = [x_1, x_2, \cdots, x_n]^T \) is the design variable, and \( \varepsilon \) is the fitting error. A quadratic polynomial function can be considered to construct the regression model for the desired response, which is expressed as:

\[
\hat{y}(x) = \beta_0 + \sum_{i=1}^{n} \beta_i x_i + \sum_{i=1}^{n} \beta_{ii} x_i^2 + \sum_{i<j}^{n} \beta_{ij} x_i x_j \tag{12}
\]

where \( \beta_0 \) is a constant, \( \beta_i, \beta_{ii}, \text{ and } \beta_{ij} \) are the coefficients of linear, quadratic, and interaction terms, respectively. The results of experiments in Table 5 were used to determine the coefficients of equation (12) by regression analysis. Then, the quadratic regression equation for the central pressure \( P_c \) in terms of four actual factors was constructed as:

\[
P_c = 502.29404 - 272.21716d - 9.95853a - 1.80471P_1 + 1.03674P_2 + 1.92831da + 0.89505dP_1 - 0.67602dP_2 + 5.14847 \times 10^{-3}aP_1 + 9.40575 \times 10^{-3}aP_2 - 2.81634 \times 10^{-3}P_1P_2 + 50.84372d^2 + 0.088283a^2 + 5.42093 \times 10^{-4}P_1^2 + 2.69917 \times 10^{-3}P_2^2 \tag{13}
\]
Results and discussion

Analysis of regression equation

To examine the accuracy and validity of the regression model developed above, an analysis of variance (ANOVA) was presented in Table 6. The main criterion used to check the fitting accuracy of response surface regression model is the complex correlation coefficient $R^2$. As shown in Table 6, the $R^2$ value (0.9824) and the adjusted $R^2$ value (0.9659) are both close to 1. The difference between the adjusted $R^2$ value and the predicted $R^2$ value (0.8684) is less than 0.2. These indicate that the regression model sufficiently represents the relationship between design variables and the response. The adequate precision value of 33.025 is much greater than 4, which illustrates the model has sufficient reliability.

Table 6 shows that the regression model formed for the central pressure $P_c$ is considered as extremely significant by taking into account that $p$-value of the model is less than 0.01. Moreover, the changes of the linear terms that include annular air hole diameter $d$, horn flare angle $\alpha$, annular air pressure $P_1$, and shaping air pressure $P_2$ have extremely significant influences on the central pressure $P_c$ ($p < 0.01$). The interaction term $(AC)$ of annular air hole diameter $d$ and annular air pressure $P_1$, the interaction term $(AD)$ of annular air hole diameter $d$ and shaping air pressure $P_2$, and the interaction term $(CD)$ of annular air pressure $P_1$ and shaping air pressure $P_2$ also have extremely significant influences on $P_c$ ($p < 0.01$).

In addition, Figure 10 shows the externally studentized residuals of the central pressure $P_c$, where the residual points fall almost on a straight line. This signifies that the errors are distributed normally and present no obvious pattern or unusual structure, implying that the terms mentioned in the quadratic regression model are significant.

Interaction effects of design parameters

With the aforementioned statistical analysis, it is concluded that the response surface regression model given in equation (13) is well fitted and valid within the ranges of the design parameters. Hence, the model can be used to predict the changing trend of the central pressure $P_c$. 

![Figure 10. Normal plot of residuals for the central pressure.](image)
Figures 11 to 16 show the response surfaces and respective contour plots that intuitively illustrate the interaction effects between two design parameters on the central pressure $P_c$ when the other parameters remain middle level.

From Figure 11, it can be seen that the central pressure $P_c$ rises with the increments of annular air hole diameter $d$ and horn flare angle $\alpha$. Compared with the horn flare angle $\alpha$, annular air hole diameter $d$ has a stronger effect to elevate the central pressure $P_c$. This is because when annular air hole diameter $d$ is increased, the flow rate of the spray gas is more correspondingly, which exacerbates the pressure acted on the central region of the target plate. This will induce the overspray to occur easily. As shown in Figure 12, when annular air hole diameter $d$ is at a lower level, the central pressure $P_c$ also increases slowly with the enlargement of annular air pressure $P_1$. However, the excessive $P_c$ is sharply produced when annular air hole diameter $d$ and annular air pressure $P_1$ reach higher levels simultaneously. It is inferred from Figure 13 that the central pressure $P_c$ decreases gradually and then increases gradually with the increase in shaping air pressure $P_2$ when annular air hole diameter $d$ is at a low level. When annular air hole diameter $d$ is at a high level, the central pressure $P_c$ can be decreased rapidly by increasing shaping air pressure $P_2$. This effect can be attributed to the fact that when other parameters keep at fixed values, the increase in shaping air pressure $P_2$ will further diffuse the high-speed airflow ejected from the annular air hole, which expands the range of spray flow field. Therefore, the local pressure on the target plate will be mitigated, which can help to produce a well-distributed coating.
Figure 14 shows the change of the central pressure $P_c$ in regard to horn flare angle $\alpha$ and annular air pressure $P_1$. It is observed that the central pressure $P_c$ rises with the increases of horn flare angle $\alpha$ and annular air pressure $P_1$. To a certain extent, annular air pressure $P_1$ has a more significant effect on the central pressure $P_c$ in comparison to horn flare angle $\alpha$, since too much annular air pressure $P_1$ exerted aggravates the local high pressure on the plate, which results in higher central pressure. It can be seen from Figure 15 that the lower value of central pressure $P_c$ is obtained when horn flare angle $\alpha$ decreases and shaping air pressure $P_2$ increases simultaneously. Horn flare angle $\alpha$ has an impact on the central pressure $P_c$ to a degree almost the same as the shaping air pressure $P_2$. This is because when horn flare angle $\alpha$ increases, the gas ejected from the shaping air holes on both sides of the nozzle will tend to be more consistent with the gas ejected from the annular air hole, which increases the velocity component along the axial direction of the nozzle. The superposition of these gases intensifies the effect of the spray flow field to the target plate. As shown in Figure 16, the interaction between annular air pressure $P_1$ and shaping air pressure $P_2$ is significant, and it changes the influence trend on the central pressure $P_c$. When annular air pressure $P_1$ is at the low level, the minimum $P_c$ can be gained at around the middle level of the shaping air pressure $P_2$. However, the central pressure $P_c$ is inclined to decrease with the enlargement of shaping air pressure $P_2$ when annular air pressure $P_1$ is at a higher level, which relieves the local pressure on the plate acted by the gas flow from annular air hole.

From above discussion about the interaction effects of the design parameters, the characteristics of the impacts of each individual parameter and combined parameters on the pressure distribution can be roughly clarified. Compared with the other two parameters, annular air hole diameter $d$ and annular air pressure $P_1$
have similar increase-effects on the central pressure $P_c$, and their changes are more likely to affect the pressure distribution on the target plate. Besides, reducing horn flare angle $\alpha$ or increasing shaping air pressure $P_2$ is beneficial to reduce the local high pressure acted by the gas flow. However, the interaction mechanism of these design parameters on the spray flow field near the plate is complicated. It is difficult to explicitly determine how large each parameter is can be more conducive to the uniformity of the coating film. Therefore, when conducting the optimal design of the atomizer, these parameters need to be taken into account simultaneously using optimization techniques.

4.3 Optimization model

For alleviating the uneven coatings by reducing the local high-level pressure on the target plate, the central pressure $P_c$ is desired to be as low as possible. In this paper, an optimization study was conducted to determine optimum values of the design parameters corresponding to the minimum $P_c$ under the constraints of the investigated values of the design parameters. The mathematical optimization model can be described as follows:

$$\text{find } x = [d, \alpha, P_1, P_2]^T$$

$$\text{min } P_c(x)$$

$$\begin{align*}
\text{s.t.} & \quad 2.3 \text{mm} \leq d \leq 3.3 \text{mm} \\
& \quad 20^\circ \leq \alpha \leq 38^\circ \\
& \quad 140 \text{ kPa} \leq P_1 \leq 340 \text{ kPa} \\
& \quad 100 \text{ kPa} \leq P_2 \leq 240 \text{ kPa}
\end{align*}$$

The desirability function approach (DFA) incorporated in Design Expert software is one of the most important

Figure 15. Interaction effects of $\alpha$ and $P_2$ on $P_c$: (a) response surface and (b) contour plot.

Figure 16. Interaction effects of $P_1$ and $P_2$ on $P_c$: (a) response surface and (b) contour plot.
and extensively utilized techniques for the optimization of various responses. Using this method, the optimization problem was solved by employing the regression model (equation (13)) of the objective function obtained previously. Among the groups of solution results with lower central pressure, three candidate solutions that have suitable desirability were preferably selected. Then, the optimization results of central pressure $P_c$ obtained by RSM were compared with the simulation results calculated by CFD under the same condition, as presented in Table 7.

The comparisons between the predicted results obtained by RSM and the simulation results of CFD show that the maximum relative error is 3.47%. It is indicated that the regression model established in this study, relating to the objective function and the design parameters, is reliable, which can approximately substitute the CFD calculation.

### Optimization results and discussion

Referring to Table 7, and considering the complexity of the atomizer structure and the controllability of the operating conditions, the optimum combination of the design parameters in atomizer was determined as follow: annular air hole diameter $d$ is 2.4 mm, horn flare angle $\alpha$ is 21°, annular air pressure $P_1$ is 160 kPa, and shaping air pressure $P_2$ is 180 kPa.

The atomizer parameters before and after optimization as well as the corresponding central pressure $P_c$ calculated by CFD were presented in Table 8. Compared with the original atomizer, fortunately, the central pressure $P_c$ can be reduced to 94.21 Pa by RSM optimization, which gets a decrement of 44.6%. As a result, the RSM technique can be applied to the optimization design of the atomizer for mitigating the local high pressure on the target plate.

Figure 17 shows the development of the spraying process when using optimized atomizer. It took about 3.4 ms for the droplets to spray from the nozzle to reach the target plate. After 7.6 ms, the spraying pattern of the coatings on the plate was basically formed.

According to references[9,40] unevenness in spray coatings is mainly related to the atomization performance. The smaller the droplet diameter is, the more the amplitude of the unevenness is decreased. To verify

### Table 7. Candidate solutions and result verification.

| Number | Design parameters | Central pressure $P_c$ (Pa) |
|--------|-------------------|-----------------------------|
|        | $d$ (mm) | $\alpha$ (°) | $P_1$ (kPa) | $P_2$ (kPa) | Predicted | Simulated | Relative error (%) |
| Candidate 1 | 2.422 | 21.280 | 156.341 | 174.466 | 91.303 | 94.172 | 3.05 |
| Candidate 2 | 2.381 | 21.395 | 156.204 | 178.176 | 90.460 | 93.712 | 3.47 |
| Candidate 3 | 2.366 | 20.795 | 168.642 | 182.251 | 91.249 | 93.875 | 2.80 |

### Table 8. Comparison of the atomizers before and after optimization.

| Type                  | Design parameters | $P_c$ (Pa) |
|-----------------------|-------------------|-------------|
|                       | $d$ (mm) | $\alpha$ (°) | $P_1$ (kPa) | $P_2$ (kPa) | $P_c$ (Pa) |
| Original atomizer     | 2.8     | 25     | 250     | 120     | 170.04 |
| Optimized atomizer    | 2.4     | 21     | 160     | 180     | 94.21  |

![Figure 17. Development of the spraying process when using optimized atomizer.](image)
the optimized atomizer can improve the atomization performance and the uniformity of coatings, the size and the corresponding number of the droplets that impinge on the target plate were collected and counted when the spraying time reaches 0.4 s. The droplet size distributions of the original and optimized atomizer were derived from the calculation under the same boundary conditions. As shown in Figure 18, before the optimization, the droplet sizes mostly distributed in the range of 30 to 65 \( \mu \text{m} \), taking a percentage of 79.9%. This indicates that most of the droplets have a large size range, which is not conducive to the uniformity of droplets on the plate. However, the optimized atomizer could produce finer droplets with a diameter of around 35 \( \mu \text{m} \) due to the adequacy and homogenization of the airflow diffusion in the space. These tinier droplets account for about 37.2% of the total number, which deposit on the plate to help form a uniform and dense coating.

**Confirmation experiments of spraying coatings**

After the structure and operating parameters of the optimized atomizer were determined, the final step is conducting the experiment of spraying coatings to confirm the effectiveness of the optimized atomizer. The air cap of the optimized atomizer that was fabricated in the machining workshop is shown in Figure 19(b). The experiment apparatus for spraying coatings was consists of air source system, paint supply system, and traverse system, as sketched in Figure 20. The atomizer was mounted on the bracket and its direction was vertically downward. The target plate that was placed under the atomizer is steel. By using the terminal device, the atomizer can be moved up and down through the traverse system. The distance between the atomizer and the plate was adjusted to 200 mm. The red paint was transported by the diaphragm pump, and its flow rate was controlled to 300 mL/min by a liquid flow meter. By controlling the piezometers, the annular air pressure and the shaping air pressure for the original and optimized atomizers were adjusted to the values that were shown in Table 8.

The snapshot of the spraying coating process captured by a high-speed camera (Fastcam MiniAX100-C, Photron, Tokyo, Japan) when using the optimized atomizer is shown in Figure 21. The spraying time lasted for 2 s, which was timed by a stopwatch. After the coatings on the steel plate had dried out, the thickness distributions were measured by the magneto-inductive method using a coating thickness gauge (Beijing Saibo Ruixin Technology Co., Ltd., Beijing, China). When measuring the coating film thickness along the X-axis, the measuring points were taken at an interval of 10 mm. At each point, the thickness was measured five times, and the average value was taken as the thickness. Finally, the obtained thickness value divided by 5 was seen as the coating thickness at the spraying time of 0.4 s.

The thickness value derived from the simulation is that of the wet coating film. When compared to the measured data of the dry coating film, the thickness of wet coating film should be converted to the dry one through the following equation:\[ h_2 = h_1 \times V_S \] where \( h_1 \) is the thickness of wet coating film, \( h_2 \) is the thickness of dry coating film, and \( V_S \) is the content of solid in paint volume, here considering \( V_S = 0.43 \).

Figure 22 compares the simulated and experimental spray patterns of the original and optimized atomizers. The shape and the size of simulated coating film are similar to that of experimental results for both two atomizers. Compared with the original atomizer, the optimized one has a wider spray range, which can not only avoid the overspray to get a more uniform coating but also improve the spraying efficiency.

The thickness distributions of the dry coatings along the X-axis obtained from the simulation and experiment for both original and optimized atomizer are compared in Figure 23. The measured data with standard
deviation are slightly lower in the center and higher on both sides than that of the simulated results for two atomizers. The main reason is that the wet painting would slightly spread to both sides under the effect of gravity during the drying process. Nevertheless, the simulated results of dry coatings still show general agreement with the experimental data. Additionally, no matter for the simulation or the experiment, the coating thickness distribution of the optimized atomizer spreads out more uniformly than that of the original one. Specifically, it was assumed that half of the maximum coating thickness along the X-axis is the effective painting film in the simulation. As such, the effective coating lengths of the original and optimized atomizer are 71.5 and 110.4 mm, respectively. The effective coating length is increased by 54.4% after the optimization design, expanding the range of spray coatings. The experimental data show similar behavior. The results discussed in the confirmation experiment illustrate that the RSM-based optimal design of the pneumatic atomizer developed in this paper, for obtaining a more uniform coating, is feasible.

Conclusions

When using a pneumatic atomizer, the local high-level pressure occurred to the target plate is the incentive of uneven coatings. An optimal design for the structure and operating parameters in atomizer has been performed to produce a well-distributed coating by reducing the central pressure $P_c$. The RSM and CFD calculation are employed to construct the regression model that expresses the relationship between the objective function and the design variables. By using this regression model, the optimization problem is solved to determine optimum values of the design parameters that minimize $P_c$. The conclusions are drawn as follows:

1. The velocity data measured by the hot-wire anemometry experimentally verify the numerical model, which lays a foundation for later optimization study. The ANOVA results show the regression model is valid and significant since the $R^2$ and the adjusted $R^2$ values are close to 1, the difference between the adjusted $R^2$ and the predicted $R^2$ values is less than 0.2, and the $p$-value is less than 0.01.

2. The response surface graphs illustrate the interaction effects of the design parameters on the
central pressure $P_c$. The interaction mechanism of these parameters is complicated. It is difficult to specifically determine how large each parameter is can help to improve the uniformity of coatings unless employing the optimization technique.

(3) The optimization results obtained by DFA are in good agreement with the simulation results of CFD, which indicates that the regression model can substitute the numerical simulation. The optimized result of design parameters is determined as follow: annular air hole diameter $d$ is 2.4 mm, horn flare angle $\alpha$ is 21°, annular air pressure $P_1$ is 160 kPa, and shaping air pressure $P_2$ is 180 kPa. The central pressure $P_c$ of the optimized atomizer gets a decrement of 44.6%, which reduces the local high pressure on the plate.

(4) After RSM optimization, the atomizer can produce finer droplets with a diameter of around 35 $\mu$m, depositing on the plate to form a more uniform coating as well as alleviate the overspray. The confirmation experiment indicates that the simulated coating thickness distributions agree with the experimental data. The effective coating length of the optimized atomizer is increased by 54.4%. Thus, the optimal design of the atomizer developed in this paper can facilitate the uniform coatings and provide industry reference for optimizing pneumatic atomizers.

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