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# Optimization of Technological Parameters for Cold Spraying Using the Response Surface Method

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**Abstract.** Cold spray technology can obtain coatings in a solid state, which is suitable for deposition protective and restorative coatings. Currently, most of the research in cold spraying is based on a single-factor analysis to explore the law. However, the interaction effect of multiple factors is more scientific. In this study, the response surface method (RSM) was used to optimize the technological parameters of cold spraying. A multi-factor and multi-level quadratic regression model was established for gas temperature, pressure, and particle diameter of outlet velocity, and the process parameters were optimized. The results showed that the gas temperature, particle diameter, and gas pressure have significant effects under a single factor. Also, under the interaction of multiple factors, the P-value of the quadratic regression model was less than $1 \cdot 10^{-4}$, and the $R^2$ of the model was 0.9626, indicating that the curve fitting is good and the model has good credibility. The interaction between gas pressure and gas temperature is significant, while the interaction between gas temperature and powder diameter, gas pressure, and powder diameter are insignificant. Moreover, the parameter error between the optimized parameters through response surface analysis and the actual numerical simulation is 0.76 %, indicating high accuracy.

**Keywords:** cold spray technology, single factor, interaction effect, response surface analysis, quadratic regression model.

## 1 Introduction

Cold spraying technology [1] is a new surface technology that produces a process of high-speed collision with substrate and formation of a coating, and it is mainly applied for surface repair of components and protection of coating or additive manufacturing applications [2, 3].

The parameters of cold spraying technology are relatively complex because too many parameters affect the deposition effect. There are three major categories. The first category is mainly about the structural parameters of parts in the cold spraying system and equipment; the second category is mainly about the fluid dynamics and other parameters of the powder flowing through the nozzle path, including temperature, pressure, propulsion, inherent gas characteristics; the third category is mainly the process parameters of powder deposition on the surface of the substrate. In the current study, most studies consider a single factor to seek the law or fitting curve [4, 5], ignore the interaction among multi-factor, and fail to consider the nozzle outlet velocity in multiple factors and levels.

The prediction of particle velocity under multi-factor interaction is more reasonable and has scientific significance. Hence, this study on muti-parameters will provide a new idea and theoretical guidance for cold spraying technology.

This work chooses a rectangular nozzle as the structural model, aiming to optimize and explore its influencing parameters with the goal of maximum exit velocity.

## 2 Literature Review

There have been many studies on the parameters of the cold spraying process by related researchers, but they are mainly based on single-factor analysis, mainly involving geometric parameters, particle motion parameters, and particle deposition parameters. Most cold spraying nozzles adopt a circular section [6]. There are many researchers on circular cross-sections, and their geometric parameters mainly focus on the contraction section, expansion section, and throat size.

Since the circular nozzle is inefficient for small rotating parts in practical engineering applications, and the rectangular section nozzle can reflect its advantages [7], researchers have focused on non-circular cross-section studies.

For example, the work [8] analyzed the influencing factors of multi-channel cold spray nozzles and found that the powder injection pressure, particle size, recovery coefficient, and internal channel position are analyzed, which affect the particle trajectory. Many researchers are also studying particle deposition parameters, and the work [9] proposed a nozzle that can be adjusted. In addition, the powder feeding position helps improve the deposition efficiency of powder. The work [10] showed that particle impact deformation is an important factor affecting the residual stress distribution of cold spray coatings. A review of numerical simulation studies on residual stress in coatings was conducted, and the relationship between particle deformation and residual stress was analyzed. The work [11] shows that at elevated temperatures (more than 200 °C), oxide glaze layers formed on both coatings were composed of $WO_3$, $TiO_2$, and $CoWO_4$, indicating high temperature is suitable for forming a composed coating. The above researchers analyzed cold spray parameters as a single factor, while for parameter optimization methods, the work [12] provides a multi-parameter optimization method to solve the complex problems existing in existing technologies. The work [13] optimizes genetic algorithms and concludes that they can also be applied in cold spraying.

This work introduces the Response Surface Method and uses a 90° angle nozzle as the numerical simulation model. Three essential parameters are selected as the research objects to seek the optimal parameters, thereby expanding the optimization parameter methods in cold spraying and having a particular theoretical reference value.

## 3 Research Methodology

This study was selected for 90° rectangular section nozzles because 90° is better than 45° and 60° [14, 15]. The SolidWorks / Flow Simulation module numerically simulates airflow and powder flow to explore the single-factor influence value.

Then, the Design Expert software was used to analyze the three key process parameters (propelling gas temperature, propelling gas pressure, and particle diameter) affecting particle outlet velocity as independent variables. The particle outlet velocity was taken as the dependent variable, the quadratic regression equation of the response surface was established, and the interaction among various factors was analyzed to obtain the optimal process parameters. Finally, the feasibility and accuracy of response surface analysis were verified by comparing the optimized parameters with numerical simulation parameters.

The 90° cold spraying nozzle mainly comprises air intake, contraction, and throat and expansion sections. The throat adopts a 90° structure. The throat section inlet and outlet adopt a length of 6 mm, a width of 3 mm, and a circular arc chamfering of 10 mm and 5 mm, respectively, in the middle.

The boundary conditions in the numerical simulation process are as follows: the influence of turbulence is considered (turbulence intensity is 2 %, and the inner wall conditions are adiabatic and smooth). The propelling gas selects nitrogen ($N_2$), the internal cavity, and excludes the internal non-flowing area are selected. The inlet of the contraction section was selected as the pressure inlet (0.8–1.0 MPa), the initial nitrogen temperature was 800–1100 K, and the outlet of the expansion section was set as the pressure outlet (0.1 MPa).

Before the multi-factor interaction analysis, the factorial analysis should be carried out first. This study selected three major factors for univariate analysis, and their levels were determined. Due to the collision speed being mainly composed of propulsion gas characteristics of particles, particle characteristics, spraying distance, and expansion length influence [16], this study has identified the nozzle structure and nitrogen, assuming that the spray distance is zero, that is, the outlet velocity of the nozzle is studied. The next test design scheme mainly analyzes propulsion gas and particle characteristics, further refining the single factor: nitrogen temperature, nitrogen pressure, and particle diameter.

In addition, the deposition conditions are considered in this study, and the high and low levels are determined when the deposition velocity is satisfied. The critical velocity is the key factor for the deposition, and its formula can be theoretically calculated using the following formula:

$$V_{crit} = \sqrt{C_P(0.7T_m - T_i)}, \quad (1)$$

where $T_m$ – the melting point; $T_i$ – the collision temperature; $C_p$ – the specific heat.

Titanium powder was selected for this study. The material parameters of the titanium particles are shown in Table 1.

Table 1 – Material properties

| Material | Specific heat, J/(kg·K) | Melting temperture, ℃ | 70 % of melting temperature, ℃ |
|---|---|---|---|
| Titanium | 452 | 1670 | 1169 |

For the single factor of nitrogen temperature affecting particle velocity, the range of 800–1100 K was selected as the preheating condition of nitrogen. Since there are many injected particles, the particle exit velocity affects the collision deposition directly. In this study, the average velocity of particles was taken as the outlet velocity of particles, and the lowest temperature under deposition conditions was taken as the low level (–1), 1000 K as the middle level (0) and 1100 K as the high level (+1). The gas pressure was 1 MPa, and the powder injection pressure was 0.71 MPa, the specific parameters are shown in Table 2.

Table 2 – Outlet velocity parameters of titanium particles at different temperatures

| Parameter | Gas pressure, MPa | | | |
|---|---|---|---|---|
| | 0.8 | 0.9 | 1.0 | 1.1 |
| Maximum powder velocity $V_{max}$, m/s | 562 | 580 | 593 | 620 |
| Average powder velocity $V_{average}$, m/s | 544 | 561 | 570 | 577 |
| Average powder temperature $T_{average}$, K | 761 | 750 | 748 | 747 |
| Powder injection pressure, MPa | 0.60 | 0.65 | 0.70 | 0.78 |
| Critical velocity $V$, m/s | 555 | 559 | 560 | 560 |
| Deposition | no | yes | yes | yes |
| Level code | – | (–1) | (0) | (+1) |

For the single factor of nitrogen pressure affecting particle velocity, under the deposition conditions, 0.9 MPa was selected as the low level (–1) and 1.1 MPa as the high level (+1). The specific parameters are shown in Table 3.

Table 3 – Outlet velocity parameters of titanium particles under different inlet pressures

| Parameter | Powder diameter, μm | | | |
|---|---|---|---|---|
| | 15 | 20 | 25 | 30 |
| Maximum powder velocity $V_{max}$, m/s | 665 | 624 | 596 | 570 |
| Average powder velocity $V_{average}$, m/s | 635 | 601 | 576 | 558 |
| Average powder temperature $T_{average}$, K | 808 | 836 | 854 | 870 |
| Critical velocity $V$, m/s | 535 | 523 | 516 | 508 |
| Deposition | yes | yes | yes | yes |
| Level code | – | (–1) | (0) | (+1) |

For the single factor of particle diameters affecting particle velocity, the study [14] shows that when the particle flow diameter is greater than 15 μm, the wall attachment effect disappears, the particle flow is mainly affected by inertia, and the influence of the airflow field on the final trajectory of the particle flow is small. Therefore, at least 15 μm titanium powder was selected in this study.

The 20 μm titanium powder was selected for the single-factor nitrogen temperature and pressure analysis. In this study, 20 μm was selected as the low level (–1), and 30 μm was selected as the high level (+1).

The initial parameters were gas temperature of 1000 K, gas pressure of 1 MPa, and particle inlet pressure of 0.71 MPa. The specific parameters are shown in Table 4.

As shown from the average velocities in Tables 2–4, there is a linear relationship between the influences of every single factor within a specific range, and the order of each single influencing factor is that gas temperature is more significant than particle diameter.

Table 4 – Outlet velocity parameters of titanium particles with different particle diameters

| Parameter | Gas temperature, °C | | | |
|---|---|---|---|---|
| | 800 | 900 | 1000 | 1100 |
| Maximum powder velocity $V_{max}$, m/s | 565 | 593 | 624 | 656 |
| Average powder velocity $V_{average}$, m/s | 530 | 570 | 601 | 625 |
| Average powder temperature $T_{average}$, K | 666 | 748 | 836 | 923 |
| Critical velocity $V$, m/s | 592 | 560 | 523 | 484 |
| Deposition | no | yes | yes | yes |
| Level code | – | (–1) | (0) | (+1) |

In contrast, particle diameter is more significant than gas pressure. Therefore, the variation rules of particle velocity under the condition of a single factor are different. The prediction of particle velocity under multi-factor change is more scientific, reasonable, and of practical significance.

Response surface methodology (RSM) combines mathematical and statistical methods, often applied to find the optimal process parameters in multi-parameter systems [17–20]. RSMs based on Box Behnken design, combining single factor numerical results, the test Design Expert software was used to set the inlet pressure $P$, the advance temperature $T$, the particle diameter $D$ as the independent variable, and the outlet velocity as the dependent variable to construct a three-factor, three-level quadratic regression equation, and its response model was:

$$y = \beta_0 + \sum_{i=1}^{m}\beta_i x_i + \sum_{i=1}^{m}\beta_{ij} x_j + \sum_{i=1}^{m}\beta_{\text{ii}} x_i^2 + \varepsilon, \quad (2)$$

where $y$ – the response value of the regression equation; $X_i$, $X_j$ – independent variables; $m$ – the number of independent variables; $\beta_0$ – the regression intercept; $\beta_i$ – the linear effect of $X_i$; $\beta_{ij}$ – the interaction effect of $X_i$ and $X_j$; $\beta_{ii}$ – the secondary effect of $X_i$; $\varepsilon$ – random error.

## 4 Results

The high (+1) and low (–1) levels of single factors (gas temperature, gas pressure, and particle diameter) were respectively input into experimental Design Expert software, and the experimental scheme and test results obtained are shown in Table 5.

Table 6 presents the results of the variance analysis.

Table 5 – Test analysis scheme and results

| Run | High and low level code | | | Actual value | | | Powder velocity $V$, m/s |
|---|---|---|---|---|---|---|---|
| | Gas temperature $T$, K | Gas pressure $P$, MPa | Powder diameter $D$, µm | Gas temperature $T$, K | Gas pressure $P$, MPa | Powder diameter $D$, µm | |
| 1 | +1 | 0 | –1 | 1100 | 1.0 | 20 | 625 |
| 2 | –1 | –1 | 0 | 900 | 0.9 | 25 | 541 |
| 3 | –1 | +1 | 0 | 900 | 1.1 | 25 | 547 |
| 4 | 0 | +1 | +1 | 1000 | 1.1 | 30 | 557 |
| 5 | 0 | 0 | 0 | 1000 | 1.0 | 25 | 576 |
| 6 | 0 | 0 | 0 | 1000 | 1.0 | 25 | 576 |
| 7 | 0 | 0 | 0 | 1000 | 1.0 | 25 | 576 |
| 8 | 0 | 0 | 0 | 1000 | 1.0 | 25 | 576 |
| 9 | +1 | +1 | +1 | 1100 | 1.0 | 30 | 560 |
| 10 | 0 | 0 | +1 | 1000 | 0.9 | 30 | 554 |
| 11 | +1 | +1 | 0 | 1100 | 1.1 | 25 | 615 |
| 12 | –1 | –1 | +1 | 900 | 1.0 | 30 | 525 |
| 13 | +1 | +1 | 0 | 1100 | 0.9 | 25 | 583 |
| 14 | –1 | –1 | –1 | 900 | 1.0 | 20 | 570 |
| 15 | 0 | 0 | –1 | 1000 | 0.9 | 20 | 600 |
| 16 | 0 | 0 | –1 | 1000 | 1.1 | 20 | 606 |
| 17 | 0 | 0 | 0 | 1000 | 1.0 | 25 | 576 |

Table 6 – The results of the variance analysis

| Source | Sum of squares | df | Mean square | F-value | P-value |
|---|---|---|---|---|---|
| Model | 11 018 | 9 | 1224.3 | 46.77 | < 0.0001 |
| $A$ – Gas temperature $T$ | 5000.0 | 1 | 5000.0 | 191.0 | < 0.0001 |
| $B$ – Gas pressure $P$ | 276.13 | 1 | 276.13 | 10.55 | 0.0141 |
| $C$ – Powder diameter $D$ | 5253.1 | 1 | 5253.1 | 200.7 | < 0.0001 |
| $A{\cdot}B$ | 169.00 | 1 | 169.00 | 6.460 | 0.0386 |
| $A{\cdot}C$ | 100.00 | 1 | 100.00 | 3.820 | 0.0916 |
| $B{\cdot}C$ | 2.2500 | 1 | 2.2500 | 0.086 | 0.7779 |
| $A^2$ | 199.00 | 1 | 199.01 | 7.600 | 0.0282 |
| $B^2$ | 23.750 | 1 | 23.750 | 0.910 | 0.3726 |
| $C^2$ | 3.2200 | 1 | 3.2200 | 0.120 | 0.7360 |
| Residual | 183.25 | 7 | 26.180 | – | – |
| Lack of fit | 183.25 | 3 | 61.080 | – | – |
| Error | 0.0000 | 4 | 0.0000 | – | – |
| Total | 11 202 | 16 | – | – | – |

In this case, the regression equation is as follows:

$$Y = 576 + 25{\cdot}A + 5.88{\cdot}B - 25.63{\cdot}C + 6.5{\cdot}A{\cdot}B -$$

$$- 5{\cdot}A{\cdot}C - 0.75{\cdot}B{\cdot}C - 6.88{\cdot}A^2 + 2.37{\cdot}B^2 + 0.88{\cdot}C^2, \quad (3)$$

where $A$ – the gas temperature; $B$ – the gas pressure; $C$ – the particle diameter.

The lack of fit is not significant. The determination coefficient $R^2$ of the regression equation is 0.9626, and the correction coefficient $R^2 = 0.7383$.

These results indicate that the regression model can well explain the powder velocity's response value variation.

The model F-value of 46.77 and P-value of 0.0001 (less than 5 %) imply that the model is significant.

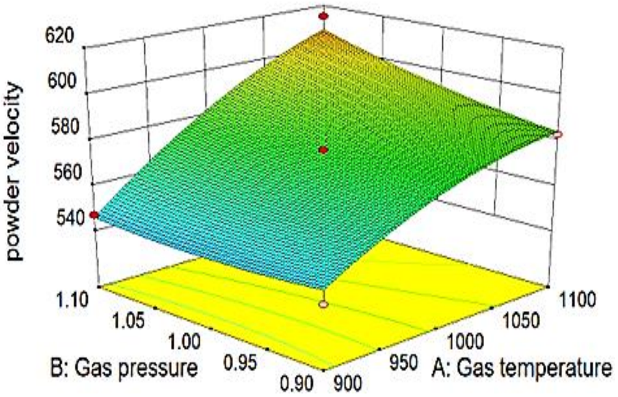
The optimized parameters are imported into the Flow Simulation Module of SolidWorks for numerical simulation verification.

Figure 1 represents the response surface analysis of three factors' interaction under $N_2$ conditions.

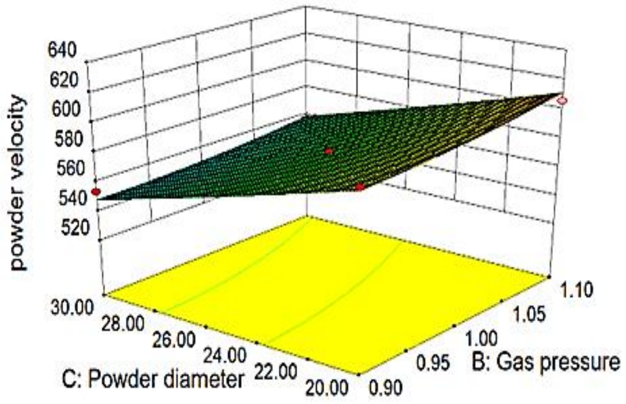
Figure 2 represents the desirability of the optimized value.

Taking the maximum particle velocity as the target, the optimized data is shown in Figure 3, and the optimal speed is predicted to be 641 m/s.

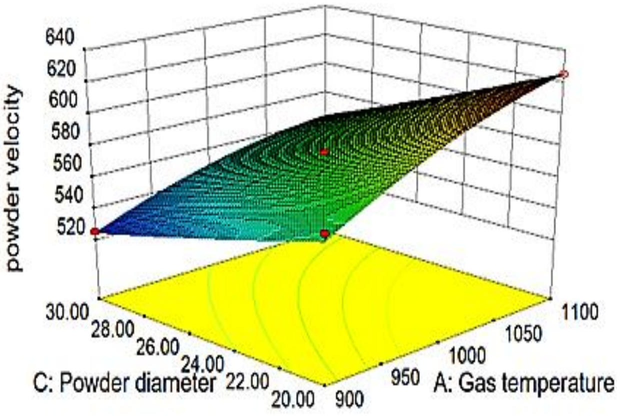
The simulation results (Figure 4) show that the average velocity of the particles was 645 m/s with an error of 0.76 %.



a



c



b

Figure 1 – Response surface analysis of three factors interaction under $N_2$ conditions: *a* – *A* and *B* factors interaction influence; *b* – *A* and *C* factors interaction influence; *c* – *B* and *C* factors interaction influence cure

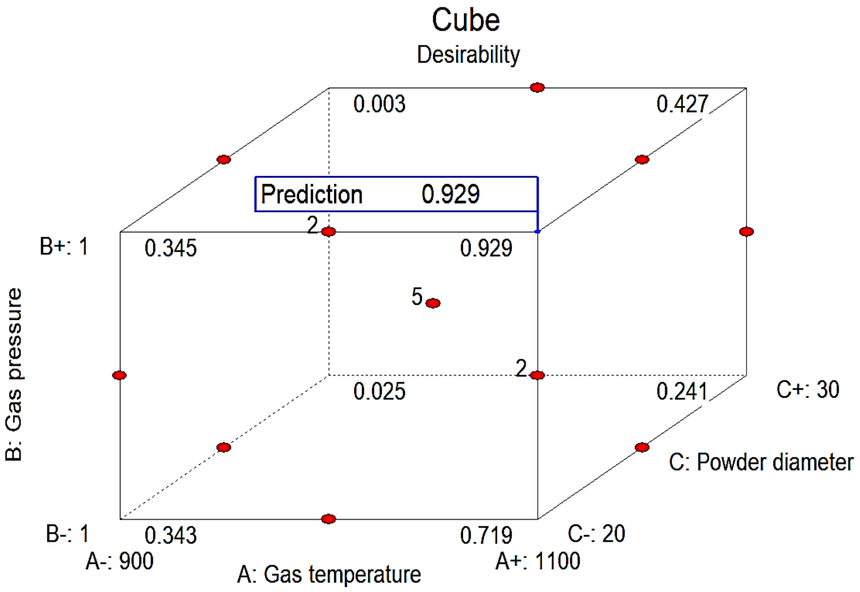


Figure 2 – The desirability of optimized value

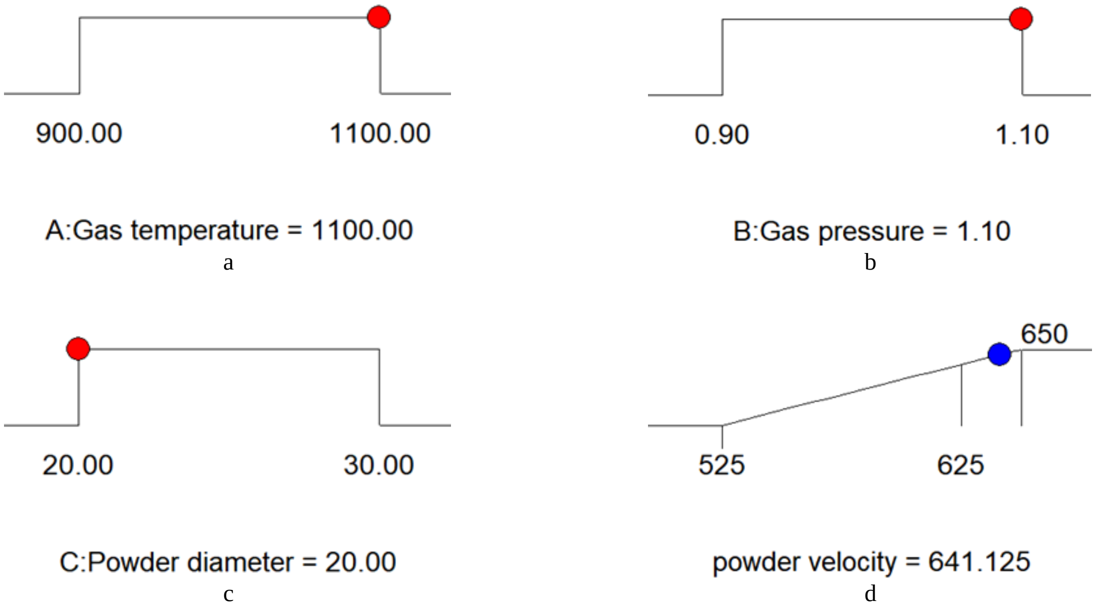


Figure 3 – The optimum parameters of maximum outlet velocity obtained by nitrogen as propellant gas:
*A* – optimal temperature; *B* – optimal pressure; *C* – optimal particle diameter;
*D* – response speed under optimal conditions

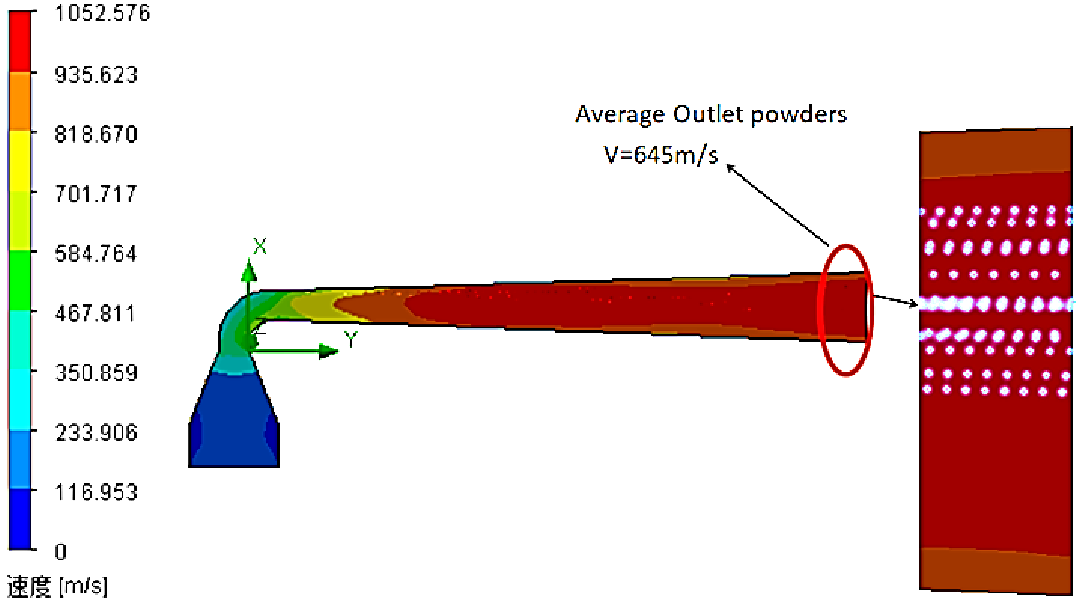


Figure 4 – Fluid velocity distribution nephogram and particle trajectory

Therefore, the response surface analysis was highly accurate.

## 5 Discussion

As shown in Table 6, the P-values of A and B are all less than 0.001 (less than 0.05), and the P-values of C are 0.00141 (less than 0.05), indicating that the single factor significantly affects particle velocity.

The P-value of $A{\cdot}B$ is 0.0386 (less than 0.05), indicating that the interaction between temperature and pressure is apparent, while the P-value of $A{\cdot}C$ is 0.0916 (greater than 0.05), and the P-value of $B{\cdot}C$ is 0.7779 (greater than 0.05), indicating that the interaction between temperature and particle diameter, gas pressure and particle diameter is not apparent.

As shown in Figure 1, the order of influence of the three factors is that gas temperature is more significant than powder diameter, and powder diameter is more significant than gas pressure.

Figure 2 shows that the optimal value is obtained with a large probability (92.9 %).

## 6 Conclusions

It is feasible to optimize the process parameters of cold spraying using the response surface analysis method, and the regression model has high accuracy. It can analyze the velocity parameters by a single factor and the influence of cold spraying parameters by multi-factor and multi-level, which has a particular theoretical reference value.

Under the action of a single factor, temperature, pressure, and particle diameter have significant effects on particle velocity, respectively, and the order of influence is that temperature is more significant than powder diameter, and powder diameter is more significant than gas pressure.

Under the interaction of multiple factors, the interaction between temperature and pressure is evident, while the interaction between temperature and particle diameter, gas pressure, and particle diameter is not apparent.

The quadratic regression model established in this study can reflect the response value of the outlet velocity well by comparing the optimized parameters after RSM with the actual velocity parameters.

Overall, due to the error of 0.76 %, the response surface quadratic regression model has high accuracy.

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