Study on Parameters of a New Gas–Water Spray in Ore Pass Dedusting Based on Experiment and Numerical Simulation

Yapeng Wang, Zhongan Jiang, Feng Xu, Jiuzhu Wang, Guoliang Zhang, and Fabin Zeng

ABSTRACT: To solve the problem of ore unloading dust in ore pass crosscuts, the atomization characteristics of a new gas–water spray and the effect of the ore discharge airflow on the spray effect were studied by experiments, and the installation position of the spray nozzle in the crosscut was determined by numerical simulation. The results show that when the gas–water flow ratio is 100–150, the atomization effect is the best. In this situation, the droplet size can be less than 28 μm. The impact airflow induced by ore unloading has a great influence on the size of the spray droplets, and the dust-collecting ability of the spray is negatively correlated with the impinging airflow. The best location for the spray is 5 m away from the wellhead. At this position, the impact airflow is less than 1.5 m/s, which can ensure that the total dustfall rate of the gas–water spray is 67% and that of the respiratory dust is 34%.

1. INTRODUCTION

An ore pass is a very important transportation form in metal mines. As a unique form of transportation, the ore pass relieves the pressure of transportation, achieving centralized production and transportation in mines. The transportation problem is solved by a multilevel ore pass, but it also increases dust pollution. With the increase of mining depth, the drop in each level increases. When the upper level is unloading, a large amount of dust enters the lower level because of the ore unloading airflow. After the dust enters the mine production system, it not only causes pollution of the working environment but also affects the health of the workers. With the continuous improvement of the national occupational health system, the number of coal mine pneumoconiosis patients has been controlled in recent years. However, the number of dust diseases caused by the metal industry has increased slightly.1–5 The increase in the number of patients is shown in Figure 1. Therefore, it is imminent to treat dust pollution in metal mines. Through the research on the existing dedusting technology, spray dustfall is the most important way of controlling dust in mines, and the dust removal effect of sprays is better.6–11

The atomizing nozzle was developed in the automotive internal combustion engine industry, and it was introduced to other industries as people acquired increasing knowledge of spray characteristics. Zhang et al.12 performed numerical simulations on air-atomizing nozzles in an oil field; Meroney13 conducted numerical simulations on the water spray interaction with dense gas plumes; Fabiano et al.14 presented experimental and theoretical investigations on liquid spray curtains, in the context of absorbing and dispersing hazardous gaseous releases; Sun et al.15 used numerical simulation tools to analyze the deposition characteristics of droplets; Zhu et al.16 conducted a series of small-scale experiments by means of a two-dimensional (2D) particle image velocimetry technique to address the lack of understanding of the dynamical behaviors and interacting mechanisms between water mist spray and high-velocity leakage gas jets. In recent years, sprays have been introduced to reduce dust. Many research studies on water sprays for coal mine dust control at home and abroad yielded. Prostański17 analyzed the water injection system designed by the KOMAG Mining Technology Institute for longwall shearsers, roadheaders, and conveyor dedusting points; Wang et al.18 studied the effect of forced airflow on the spray flow field by the ANSYS FLUENT program; the macroscopic and microscopic atomization characteristics of four well-applied solid cone nozzles with a spray pressure of 2–8 MPa based on the nozzle atomization characteristic measurement experimental device were tested by Yin et al.19 and Peng et al.20 However, there is a certain difference between metal mine dust control and coal mine dust control. Compared with coal mines, metal mines are generally dry, and dust is more likely to be generated under the action of the blowhole impact airflow.
Coal mines can use sprays and preflowing coal to reduce dust. However, the transportation of wells and metal smelting in metal mines requires a certain amount of ore water content, and metal mines are not suitable for water sprays. A new gas–water spray with less water consumption and a good atomization effect can control the dust in the ore pass.

There are many research studies about spray dustfall in coal mines, but there are only a few studies on spray dustfall in ore passes. The impact of the airflow on the study of water spray dust removal has not been considered. Therefore, the water spray dust reduction parameters in coal mines cannot be fully used in the treatment of ore pass dust. Based on the above, it is of great significance to study the application of gas–water spray dust reduction technology in the ore pass. To ignore the influence of external factors, laboratory research has become the most direct means to solve the problem of dust pollution on site. The spray parameters and their influencing factors were studied for a new adjustable-angle nozzle with a spray diameter of 1.5 mm, based on the dustproof laboratory equipment of the University of Science and Technology Beijing. The numerical simulation method is used to study the airflow distribution and wind speed variation in the crosscut of the ore pass, and the reasonable position is determined for the installation of the spray device. The research results provide a theoretical basis for the gas–water spray technology in the control of multilevel ore pass dust.

2. RESULTS AND DISCUSSION

2.1. Experimental Analysis of the Atomization Effect of Nozzles. 2.1.1. Analysis of the Influence of Gas–Water Pressure on the Atomization Effect. The smaller the droplet size, the easier it is to catch the dust in air. Therefore, the droplet size can be used as a standard to measure the ability of spray dustfall. A gas–water spray mainly uses compressed air and high-pressure water for power, and the water is broken into droplets under the action of the nozzle structure. It can be seen from the above analysis that the change of gas–water parameters is the main factor affecting the atomization effect. On the basis of the existing research results of gas–water sprays, the water pressure is set at 0.3–0.7 MPa and the air pressure is set at 0.2–0.6 MPa.21 The droplet diameter was measured by a laser particle size analyzer at different air and water pressure ratios. In this paper, D10, D50, D[4,3], and D90 are used to analyze the atomization effect of nozzles. The droplet size varies with the gas, water volume, and gas and water pressures, as shown in Figure 2.

As shown in Figure 2a,b, the proportion of droplet size below 16 μm was 10%, the proportion of droplet size below 27 μm was 50%, and that of droplet size below 39 μm was 90%. At the same time, the average size of the droplet is smaller than 28 μm. Because the dust is easily captured when the droplet size is close to the dust size, the droplet size should be reduced as much as possible by adjusting the gas–water ratio. It can be seen from Figure 2 that the larger the air pressure is, the smaller the droplet size is; hence, the best air pressure range is 0.4–0.6 MPa. Under this condition, the corresponding range of water pressure values is 0.3–0.4 MPa, the corresponding water flow range is 0.85–1.2 L/min, and the airflow range is 115–135 L/min, and the change of gas and water flow shows a negative correlation. Through the above analysis, the optimum gas–water flow ratio ranges from 100 to 150.

Besides the droplet size, the atomization angle should also be used as a criterion for judging the spray effect. A large atomization angle can reduce the use of the spray head and reduce the cost of dust reduction. On the basis of the above research, the atomization angle is analyzed in the range of air pressures 0.3–0.6 MPa and water pressures 0.4–0.7 MPa. The control variable method is used to study the change of the atomization angle under different gas–water pressures, and the atomization angle changes of the new gas–water spray is shown in Figure 3.

It can be seen from Figure 3a that the atomization angle is continuously increased in the gas pressure change interval of 0.3–0.6 MPa when the water pressure is 0.3 MPa. The increase
in air pressure causes the water to be sufficiently atomized at the nozzle, and the atomization angle is continuously increased. It can be seen from Figure 3b that the water pressure increases from 0.4 to 0.7 MPa when the gas pressure is 0.5 MPa, and the atomization angle of the nozzle first increases, then decreases and finally stabilizes. The nozzle has a maximum atomization angle of 76° and a minimum of 66°. With increasing water pressure, the water supply increases, and more droplets are formed to make the air pressure utilization higher and, therefore, the atomization radius becomes larger.

Through the above parameter analysis, when the water pressure is 0.4 MPa and the air pressure is 0.6 MPa, the spray atomization angle is the largest and the maximum value is 80°.

2.1.2. Analysis of the Influence of the Volumetric Flow Ratio on Droplet Size. To achieve single factor analysis, the volumetric flow ratio of gas and water is used to analyze the influence of gas and water on the particle size change of the droplet. The relationship between the volume ratio of gas and water and the average particle size of the droplet is shown in Figure 4.

It is seen from Figure 4 that the particle size of the droplet is inversely proportional to the gas–liquid flow ratio, and the average particle size of the droplet in the range of 110–350 is less than 23.0 μm. When the gas–water flow ratio is less than

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**Figure 2.** Droplet size and gas and water flow change.
110, the influence on the particle size of the droplet is large. When the gas–water flow ratio is 110–350, the droplet change is relatively stable. The optimal gas–water flow ratio interval is consistent with the optimal particle size range determined by the gas–liquid pressure ratio in the experiment. The ratio of the droplet size to air–water flow meets the equation:

\[ D = 41.64 \left( \frac{Q_g}{Q_l} \right)^{0.11} \].

2.2. Similar Experimental Study of the Spray and Dustfall Based on the Mine Pass Environment.

2.2.1. Analysis of the Influence of Unloading Airflow on Droplet Size. When the dust is removed by the spray, the airflow of ore unloading has a great influence on it. Therefore, it is of great significance to study the influence of airflow speed on droplet size and dust removal ability. The change of the droplet size is monitored when the optimum gas–water flow ratio is 126 (air pressure of 0.5 MPa, water pressure of 0.4 MPa), and the changes of the forward wind speed are 0.0, 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 m/s. Wind speed measurement in the roadway is shown in Figure 5. The results that the droplet size is measured at different wind speeds are shown in Table 1. Taking D50 and D90 as examples, the influence of the wind speed on the droplet size change is analyzed, as shown in Figure 6.

![Figure 3. Variation of the atomization angle with gas–water pressure.](image3)

![Figure 4. Variation of droplet size with the gas–liquid ratio.](image4)

![Figure 5. Measurement of wind speed in the roadway.](image5)

| wind speed (m/s) | D10 (μm) | D50 (μm) | D90 (μm) | D98 (μm) | D[4,3] (μm) |
|-----------------|-----------|-----------|-----------|-----------|-------------|
| 0               | 17.628    | 26.533    | 37.227    | 42.440    | 27.011       |
| 0.5             | 17.971    | 27.367    | 39.621    | 48.913    | 28.106       |
| 1.0             | 18.512    | 28.623    | 40.723    | 51.648    | 29.475       |
| 1.5             | 21.614    | 29.275    | 43.892    | 56.414    | 33.652       |
| 2.0             | 23.221    | 32.962    | 49.695    | 57.704    | 34.384       |
| 2.5             | 24.104    | 33.974    | 51.658    | 68.490    | 35.173       |
| 3.0             | 24.660    | 35.395    | 55.590    | 73.596    | 38.088       |

From Table 1, it can be seen that the droplet size increases with the increase in the wind speed in the roadway under different analysis standards. The wind speed increases the collision between the droplets so that the droplets after atomization come into contact with each other, resulting in the accumulation of the droplet mass, and the droplet size increases. It can be seen from Figure 6 that the increasing wind causes the droplet size to change rapidly to exhibit two peak changes. When the wind speed is 0.5 and 2.0 m/s, it has a great influence on the particle size of the droplets, and the droplet size changes are also obvious. When the wind speed is less than 1.5 m/s, the effect of wind speed on the droplet size is not significant. Therefore, the wind speed in the roadway is less than 1.5 m/s, and the atomization effect can be ensured with a small effect on the change of droplets.

2.2.2. Study on the Influence of Ore Unloading Airflow on the Spray Dedusting Effect. To simulate the change of the flow field in the crosscut, a variable-speed fan is used to change
the airflow in the crosscut. Based on the study of the influence of wind speed on spray particle size, the effect of spray dust suppression under different wind speeds is analyzed. To analyze the interference of the airflow with the spray dust suppression after unloading, five wind speed values in the 0.5–2.5 m/s wind speed range are simulated and analyzed. A dust concentration detector was used to detect the concentration of the total dust and respirable dust before and after spraying. The monitoring results are shown in Figure 7.

As shown in Figure 7, the effect of spraying on total dust and respirable dust increases with the increase of airflow, showing a trend of first increase and then decrease. The reasons for the above phenomena are as follows: when the wind speed is low, air movement accelerates the mixing degree between the droplets and dust particles, and the probability of collecting dust by droplets increases, and the rate of dustfall increases. On the contrary, when the airflow is too large, the contact time between the dust and droplets is shortened, and the ability of spray dust suppression is weakened rapidly. When the wind speed is 1.5 m/s, the effect of dust reduction is better. The best total dust reduction rate of total dust is 67%, and that of respirable dust is 34%. Respirable dust is more affected by airflow, so the effect of spraying on respirable dust is lower than that of the total dust. It is easy to conclude that the position of the impact wind speed in the crosscut is less than 1.5 m/s to benefit spray dust reduction by analyzing the influence of wind speed on the droplet size and the dustfall rate.

2.3. Simulation and Result Discussion of Ore Unloading Airflow. The height of the ore pass is about 100 m, which is divided into four levels with a height difference of 25 m. The ore pass radius is 1.5 m, the angle between the ramp and the horizontal is 60°, and the ramp radius is 1.2 m. The crosscut is directly connected with the slope, and its section is approximately square with 4 m side length and 15 m roadway length. The model is shown in Figure 8. The vertical displacement of the runway is usually about 4000 kg, and the radius of the ore block is 0.05–0.1 m. In the first horizontal crosscut of ore pass, the speed of the inlet is set to 0.1 m/s, the second, third, and fourth sections are set as pressure outlets, and the rest of the model is set as the wall. The setting of specific parameters is shown in Table 2.

The change of the wind speed in the contact lane affects the dust-collecting ability of the gas–water spray. Therefore, it is of great significance to study the wind speed change law in the contact lane after unloading, which can provide a theoretical basis for the spray equipment installation position. It takes about 6 seconds for the ore to reach the bottom of the ore pass when it falls from the first level. The gravitational potential energy is continuously converted into the air kinetic energy during the process of ore falling. As the kinetic energy of air is accumulating continuously, the wind flow in each part of the mine is at its maximum at 6 s. Therefore, it is important to study the wind speed and wind speed direction of each part of the ore pass at 6 s. The horizontal axis section of the ore pass axis is 6 s, and the wind speed cloud map and the crosscut wind speed vector diagram are shown in Figure 9.

As seen from Figure 9a,b, the ore drop height and the amount of airflow compression in the ore pass are small, resulting in insufficient airflow in the ore pass to be pressed.
Table 2. Major Parameters in Numerical Simulations

| Name                  | Parameter Setting       | Name                  | Parameter Setting       | Name                  | Parameter Setting       |
|-----------------------|-------------------------|-----------------------|-------------------------|------------------------|-------------------------|
| CFD-DEM               | time                    | parameter setting     | max iterations /time step| 30                     | k-epsilon (2 equations) |
| solver type           | pressure-based          | hydraulic diameter    | 4 m                     | turbulent intensity    | 4.27%                   |
| gravity               | -9.81 m/s                | solution Method       | scheme (SIMPLE)         | calculated frequency   | 10                      |
| velocity inlet        | 0.1 m/s                  | pressure outlet       | gradient change         | wall                   | no slip                  |
| particle contact model | Hertz–Mindlin model      | Poisson’s ratio       | 0.4                     | particle density       | 4800 kg/m³               |
| Diameter distribution | R–R                     | particle radius       | 0.05–0.1 m              | unloading speed        | 2000 kg/s                |

3. CONCLUSIONS

In this paper, the establishment of a new mathematical model of spray droplet size determines the main parameters affecting the droplet size. The effects of gas—liquid pressure changes on droplet size, atomization angle, and axial stability of droplets were analyzed experimentally. The effects of airflow changes on droplet size and the dust-collecting ability of the spray were also studied. The numerical simulation is used to determine the variation law of the impact airflow of the ore pass, which provides a theoretical basis for the spray installation position. Based on the above research, the following conclusions are drawn:

1. The establishment of the formula for calculating the particle size of the droplets determines that the size of the gas and water flow is key to affecting the particle size of the droplets. The effect of the change in gas flow on the particle size of the droplet is greater than that of the water flow. In the three-variable analysis of air pressure, water pressure, and droplet size, the optimal atomization parameter (gas pressure range of 0.4–0.6 MPa, water pressure range of 0.3–0.5 MPa) was determined.

2. The optimum gas–water flow ratio of the new air–water nozzle ranges from 100 to 150, and the droplet size can reach less than 28 μm. The gas flow rate and the water flow rate are mutually restricted under the pressure change. If one side increases, the other will certainly decrease. When the air pressure is constant, the water flow is positively correlated with the water pressure, and when the water pressure is constant, the airflow is positively correlated with the air pressure.

3. In the optimum gas–water pressure ratio region, the atomization angle increases with the increase of the air pressure, and the maximum atomization angle is 80°. The atomization angle increases first and then decreases with the increase of the water pressure, and it is stable in the final region. The maximum atomization angle is 76°. The change of air pressure has a greater influence on the atomization angle than that of water pressure. The atomization angle can be optimized by adjusting the pressure according to the actual situation.

4. The airflow produced by the unloading of the ore pass has a great influence on the droplet size. The droplet size increases with the increase of the wind speed. The wind speed, with 2 m/s, has the greatest influence on the droplet size. The wind speed is inversely proportional to the ability of dust removal. As the wind speed increases, the dust-collecting capacity shows a tendency to increase sharply and then decrease sharply. The maximum dustfall rate was 67%, and the maximum dustfall rate of respirable dust was 34%.

5. The maximum impact airflow generated by the unloading of the ore pass is located in the fourth level,
Figure 9. continued
where the maximum wind speed is 2.5 m/s. The maximum impact wind speed of the droplet size is 1.5 m/s. It is known from the attenuation of the airflow in the crosscut that the optimum spray installation position is 5 m away from the wellhead.

4. EXPERIMENTAL SECTION AND COMPUTATIONAL METHODS

4.1. Establishment of the Gas–Water Spray Mathematical Calculation Model. The coal mine mostly uses water sprays to carry out dust control, but the water consumption of water sprays is large, and the water content of the ore is increased excessively, which affects the transportation of ore. Water sprays are not suitable for treating ore pass dust. But the new air–water spray is powered by pressurized water and compressed air. The two-stage atomization process of the spray head makes the water become a droplet with a smaller particle, which is more suitable for the treatment of ore pass dust. The structure and atomization principle of the new air–water nozzle is shown in Figure 11.

The smaller the size of the droplets produced by the air–water nozzle, the stronger the ability of the droplets to capture dust. The particle size of the droplet is the key to affecting the dust-collecting ability. The formula for calculating the average particle size of the mist by the gas–water spray is

\[
D_l = \frac{585.21}{v_g} \left( \frac{\sigma}{\rho_L} \right) + 5.97 \times 10^4 \left( \frac{\mu_L}{\sqrt{\rho_L}} \right) \left( \frac{Q_l}{Q_g} \right)^{0.45} \left( \frac{Q_l}{Q_g} \right)^{1.5} 
\]

In the above equation, \(D_l\) denotes the average droplet size, using the unit m; \(v_g\) denotes the air–liquid two-phase relative flow rate in the mixing chamber, using the unit m/s; \(\sigma\) denotes the surface tension coefficient of liquids, using the unit \(10^{-5}\) N/cm; \(\mu_L\) denotes the liquid viscosity coefficient, using the unit Pa s; \(\rho_L\) denotes the density of liquids, using the unit g/cm\(^3\); \(\delta\) denotes the liquid–gas flow ratio; and \(Q_l\) and \(Q_g\) are the volume flow rates of liquid and air, respectively, using the unit m\(^3\)/s; where \(v_g = \sqrt{v_i^2 + v_L^2 - 2v_i v_L \cos \alpha}\), \(v_i\) and \(v_L\) are the gas and liquid velocities, using the unit m/s and \(\alpha\) denotes the gas–liquid two-phase flow velocity angle.

Under constant temperature and constant pressure conditions, the fluid in the nozzle mixing chamber satisfies \(Q = v \times A\). Liquid water parameters \(\sigma = 72 \times 10^{-5}\) N/cm, \(\mu_L = \). 

Figure 9. Velocity nephogram and vector graph of the ore pass.

Figure 10. Comparative analysis of simulation data and actual data.

Figure 11. Structure and atomization principle of the new gas–water spray head.
0.00982 Pa·s, and \( \rho_\text{l} = 1.0 \text{ g/cm}^3 \). Substituting the above parameters into eq 1 reduces it to

\[
D_1 = \frac{4965.7}{\left(\frac{Q_1}{A_1}\right)^2 + \left(\frac{Q_1}{A_1}\right)^2 - 2 \cos \alpha \frac{Q_1}{A_1} \frac{Q_1}{A_1}} + 0.284
\left(\frac{1000Q_1}{Q_\text{g}}\right)^{1.5}
\]  

(2)

In the above equation, \( A_1 \) denotes the liquid injection hole area, using the unit \( \text{m}^2 \) and \( A_1 \) is the air injection area using the unit \( \text{m}^2 \). The nozzle water injection hole diameter of the experiment was 1.5 mm, \( A_1 = 1.77 \times 10^{-6} \text{ m}^2 \); the gas injection hole has a diameter of 2.0 mm, \( A_1 = 3.14 \times 10^{-6} \text{ m}^2 \); \( \alpha = 30^\circ \). Substituting the parameters into formula 2 finally simplifies it to:

\[
D_1 = \frac{4965.7 \times 10^{-6}}{9.86 + \frac{Q_1^2}{3.13} - \frac{Q_1}{3.21}} + 0.284 \left(\frac{1000Q_1}{Q_\text{g}}\right)^{1.5}
\]  

(3)

4.2. Establishment of an Experimental Platform. To test the atomization ability of the new type of gas—water sprinkler, the best spray parameters were determined, and the experimental platform for the gas—water spray test was established. The experimental platform is shown in Figure 12. The compressed air and pressurized water are supplied by the air compressor and the high-pressure pump, respectively, in the spray process. The maximum gas transmission pressure of the air compressor is 0.8 MPa, and the maximum water transmission pressure of the high-pressure water pump is 6 MPa. The air compressor and water pump are connected with a pressure gauge and a flow meter, respectively, by an air pressure pipe. Then, the air pressure pipe is directly connected to a pressure gauge and a water pressure valve. The air compressor and water pump are connected with an atomizing nozzle. The dustfall ability of the gas—water spray is determined by the atomization degree of the sprinkler. The change of gas and water ratio parameters has a great influence on the atomization degree. The best parameters can be determined through the gas—water ratio experiment, and the ability of spray dust suppression can be improved. The gas and water flow of the nozzle are controlled by adjusting the air pressure valve and the water pressure valve.

When the first level of the ore pass is unloading, the dust is brought into the crosscut by the impinging airflow generated by the ore falling process, which pollutes the working environment. Compared with the spray and dustfall in the stable air environment, the impinging airflow brings the dust into the working environment and changes the contact time between the droplet and the dust, which affects the effect of spray dust suppression. The existing research on the rate of spray dustfall is not consistent with the ore pass dedusting. Therefore, as shown in Figure 13, a spray dust reduction rate experimental crosscut is established to analyze the influence of the impinging airflow on the droplet size and the dust-collecting efficiency. To make the airflow environment similar to the scene in the experimental tunnel, a frequency conversion fan is set up in the tunnel to simulate the interaction between the dust and the spray under different wind speeds. The spray head with 30° in width installed at an angle toward the exit of the roadway was placed at a distance of 2 m from the fan. There is also a difference in the combination ability of different dust materials and spray. To reduce the error of irrelevant factors, the dust collected from field-collected dust is used for the experiment. The changes of dust concentration and dust particle size before and after spraying were monitored and analyzed with the instrument shown.

4.3. Establishment of the Theoretical Model of Numerical Simulation. Through experimental analysis, it is known that the change of wind speed affects the dust-reducing ability of the gas—water spray. The choice of the installation location of the spray dust-reducing equipment in the ore pass communication lane ensures the dust-removing ability of the spray. The analysis model of impact airflow variation of ore pass unloading is established using CFD-DEM numerical simulation software. In the simulation analysis of the ore unloading flow of the ore pass, air in the ore pass is a continuous phase. The Navier—Stokes governing equation is used to describe the mass and momentum conservation of the gas phase as

\[
\frac{\partial (\rho \varepsilon_g)}{\partial t} + \nabla \cdot (\rho \varepsilon_g \mathbf{u}_g) = 0
\]  

(4)

\[
\frac{\partial (\rho \varepsilon_g)}{\partial t} + \nabla \cdot (\rho \varepsilon_g \mathbf{u}_g) = \frac{\rho_g}{\varepsilon_g} \mathbf{v}_g \cdot \nabla P + \varepsilon_g \mathbf{v}_g \cdot \nabla \tau_{\text{gg}} - F_{\text{v6}}
\]  

(5)

In the above equations, \( \rho_\text{g} \) denotes the density of the gas phase, using the unit kg/m\(^3\); \( \tau_{\text{gg}} \) denotes the viscous stress tensor of the gas phase; \( P \) denotes the gas pressure, Pa; \( \varepsilon_g \) denotes the volume fraction of the gas phase; \( u_g \) denotes the
velocity of the gas phase, using the unit m/s; and \( F_{\text{tr}} \) denotes the interaction between the ore and gas, using the unit N. In the process of ore falling, there will be a lot of turbulence in the ore pass. The RSM turbulence model is used to describe the fluid change. The turbulence control equation is as follows

\[
\frac{\partial}{\partial t}(\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = \nabla \cdot \left( \mu \nabla \mathbf{u} + \mu_1 \left( \nabla \mathbf{u} + \nabla \mathbf{u}^T \right) \right) - \nabla p + \mathbf{f} + \Theta - \varepsilon
\]

(6)

In the above equation, \( \mathbf{i}, \mathbf{j}, \) and \( \mathbf{k} \) are the three directions of the Cartesian coordinate system; \( \mathbf{D}_j \) denotes the turbulent diffusion term; \( \mathbf{P}_j \) denotes the stress generating term; \( \Theta \) denotes the pressure strain term; and \( \varepsilon \) denotes the dissipation term.

The falling ore particles are discrete phases in the simulation process. The rotation and collision of ore particles in the ore pass can be described by Newton’s second law

\[
m \frac{dv}{dt} = F_{\text{gs}} + F_{\text{gr}} + F_{\text{a}} + F_{\text{m}} - \nabla p \mathbf{V} + mg
\]

(7)

In the above equation, \( v \) denotes the particle velocity, m/s; \( m \) denotes the mass of the particle, kg; \( F_{\text{gr}} \) denotes the aerodynamic force; \( F_{\text{a}} \) denotes the Saffman lift force, \( F_{\text{m}} \) denotes the Magnus lift force due to the particle rotation; \( -\nabla p \mathbf{V} \) denotes the pressure gradient; and \( g \) denotes the acceleration of gravity, m/s².

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### Notes
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