Research on Control of Ore Pass Dust by Unloading Time Interval and Foam Control Technology

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Abstract: To control the dust pollution caused by the unloading of a multilevel ore pass, numerical simulation and similar experiments were carried out to study the airflow and dust migration influenced by the unloading quantity and the continuous unloading at different time intervals in the ore pass. From this research, the following conclusions are drawn: when the first level of the ore pass is unloaded, the third and fourth levels are the main dust-producing positions, and the concentrations of dust in the breathing zone can reach 85 and 325 mg/m³, respectively. Increasing the unloading interval and reducing the total single unloading quantity can prevent the superposition of dust production. The foam dust removal technology can reduce the secondary dust generation caused by the backlash of the airflow in the ore pass, and the dust emission rate can reach 60% at the fourth level.

1. INTRODUCTION

Dust pollution has restricted the rapid development of mining enterprises, and dust is produced in most of the technological processes.1,2 There are also differences in the diffusion rules and hazard levels of dust particles in different industries.3−5 The dust pollution of a coal mine is more serious than that of a metal mine.6 At home and abroad, a lot of research has been carried out on the control of coal dust pollution. Wang et al.7 used numerical simulation software to analyze the airflow and dust migration during the air curtain isolation of dust of the fully mechanized coal mining face. The results show that the installation of the air curtain can effectively control the dust entering the operational area of the shearer. The rate can reach more than 70%, and the dust control effect is more obvious. Wang et al.,8 Zhou et al.,9 and Cai et al.10 used computational fluid dynamics (CFD) software to simulate the diffusion law of inhalable dust generated by multiple dust sources in the coal mine fully mechanized caving face and summarized the dust migration law, which provided a theoretical basis for dust control. Zhou et al.11 and Niu et al.12 analyzed the dust control parameters of the air curtain and determined the optimal ventilation parameters of the dust screen, which improved the excessive dust concentration of the fully mechanized mining work. To study the influence of the installation position of the air curtain on the dust diffusion law in the roadway, Wang et al.13 used the Fluent software to simulate the variation of the airflow in the roadway at different installation positions of the air curtain generator and determined the optimal ventilation and dust control parameters. Based on the particle collision, Ma et al.14 and Geng et al.15 used numerical simulations to analyze the dynamic characteristics of dust dispersion in the coal roadway, which effectively reduced the damage of coal mine dust explosion.

Compared with a coal mine, the research on the dust diffusion law of a metal mine is relatively less. Few research studies are focused on the problem of dust pollution in ore passes, and many scholars focus on the process of material falling and dust production. Esmaili et al.16,17 experimentally determined the amount of air entrainment during the falling of the particles and proposed a new theory of air entrainment prediction, which opened up new research ideas for controlling the falling dust of the particles. Uchiyama,18 Ansart et al.,19 and Wypych et al.20 analyzed the dust generation and air entrainment mechanism during the falling of the material and provided a theoretical basis for dust control through the study of the drop height. Chen et al.,21,22 Roberts,23 and Lamas et al.24 used experimental and CFD simulations to analyze dust emissions from the conveyor ore pass, which improved the ore pass structure and reduced dust production during the ore pass operation.

In the unloading process of an ore pass, a large number of ores collide and fall down in the ore pass, which has a great

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impact on the ore pass wall, causing wear, instability, and noise pollution; at the same time, the falling ore compresses the air in the ore pass to generate unloading airflow, and under the action of airflow, dust enters the contact lane, leading to serious dust pollution. Studies on the ore pass are very few, for example, airflow changes, dust generation, and diffusion. To fill the research gap on the dust production and distribution of an ore pass and to provide a theoretical basis for the dust control of the ore pass, the Lilou mine ore pass transport system of Anhui Mining Group was taken as the research background, and a numerical simulation and similar experiments were used to simulate the impinging airflow in the ore pass. The distribution characteristics and the migration law of dust are studied and analyzed.

2. RESULTS AND DISCUSSION

2.1. Simulation Results and Discussion. 2.1.1. Analysis of the Influence of Unloading Quantity on Airflow. As shown in Figure 1, the wind speed in the ore pass gradually increases with the drop height, and the maximum wind speed appears when the ore falls to the mine bunker. The ore falls to the mine bunker for 6 s, and the maximum wind speed (representation of the impact of airflow velocity) in the ore pass is 6 m/s. It is seen from the wind speed cloud diagram that the most obvious changes in the wind speed are at the first and fourth levels. The wind speed in the first level is the rapidly changing wind flow caused by the free fall of the entrained airflow. The fourth level wind speed is the accumulation of energy during the falling of the ore. In the fourth level, as the main dust-producing part of

Figure 1. Wind speed cloud map at different times.
the ore pass, the wind speed changes greatly, carrying a large amount of dust and flowing out of the wellhead.

As shown in Figure 2, the ore movement state and the flow vector comparison diagram in the ore pass are different at 2, 4, 6, 8, and 10 s, when the unloading quantity is 4000 kg. From the wind speed vector arrow and the ore drop position in the figure, when the ore does not pass the second level (4 s before the ore falls), the wind flow in the second, third, and fourth levels is consistently blown out of the ore pass port, due to the airflow carried by the ore. The wind speed in the fourth level is higher than that in the second and third levels, and it is the key part of dust prevention. When the ore falls for 6 s, a large amount of ore has passed through the second level, resulting in negative pressure in the second level, and the wind flow in the communication lane is reversed into the ore pass, so the direction of the second level changes. Due to the change in the direction of the second level, the dust removal device can adjust the working state according to the time.

The above-mentioned 4000 kg unloading quantity is used to analyze the overall variation of wind speed and direction at different positions of the ore pass during the 10 s of the ore falling. The wind speed change of the unloading port in different levels of the ore pass determines the severity of the dust pollution working area. When the quantity of unloading per second is constant, after changing the total unloading amount, the wind speed variation curve in the middle part of the different levels of the unloading port is extracted, as shown in Figure 3. It is seen from Figure 3 that the maximum wind speed at the different levels of the ore pass is proportional to the quantity of unloading. As the wind speed in the ore pass continues to accumulate, the retaining wells reach the peak from high to low. After the wind speed at each ore pass reaches its maximum, the wind speed decays more quickly, as the quantity of unloading increases. According to Figure 2, the direction of the wind flow changes due to the height of the ore falling during the unloading process, in the second level of the ore pass. It is seen from Figure 3b that as the quantity of unloading increases, the moment of the changing of the direction of the wind flows is gradually delayed in the second level. In the third level, the ore dropped at 8 s, and the

Figure 2. Wind speed vector and particle motion in the ore pass.
attenuated airflow at the ore pass gradually increased. Therefore, for the analysis of the wind flow curve, it is seen that the secondary dust will appear in the third level after the ore reaches the mine bunker.

2.1.2. Analysis of the Influence of Unloading Time Interval on Airflow. The unloading time interval is studied to control the superposition of airflow. Table 1 shows the wind speed changes at different time intervals when two unloadings are carried out (single unloading quantity is 3000 kg) in the first level.

It is seen from Table 1 that at the unloading port of each level of the ore pass, there is a tendency for the wind speed to increase first and then decrease within 8 s, with the increase of the unloading time interval. When the ore falls for 10 s, the wind speed first decreases and then increases with the increase of the unloading time interval. The wind speed decay in each level is accelerated with the increase of the unloading time interval. Analysis of the changed direction at the second level of the wind flow direction shows that when the two unloading time intervals are at least 6 s, the direction of the wind flow changes in advance, and the wind flow caused by unloading does not overlap. The movement of ore in the ore pass and the superposition of wind speed are shown in Figure 4. Through the analysis of the above data, when the unloading weight is constant, the impact of wind speed can be reduced by controlling the single unloading amount and the adjacent unloading time interval, thereby weakening the dust generation amount.

2.2. Experimental Results and Discussion. 2.2.1. Analysis of Changes in Airflow and Wind Pressure. According to the above data, when the unloading quantity is 4000 kg by numerical simulation, the variation of the wind flow in the ore pass is simulated and the airflow variation in the ore pass is summarized. To verify the reliability of the numerical simulation, the wind flow and wind pressure changes after unloading are analyzed on a similar experimental research platform. Following similar criteria, the single unloading quantity is small and the fall time is too short, and hence, it is not easy to reflect the wind speed variation law. Therefore, the experiment was carried out with a double unloading quantity (2.56 kg) and a flow rate of 0.64 kg/s. The wind speed (measuring point is a) and pressure difference (measuring points are A-D) are monitored separately during the unloading experiment. The experimental results are shown in Figures 5 and 6.

It can be seen from Figure 6 that the wind pressure of measuring point A has always a negative value, indicating that the wind flow is sucked into the ore pass in the first level. In the second level, the wind pressure difference of measuring point B is positive before 4 s, showing the ore squeezing the airflow. After 4 s, the ore passes through, causing a negative pressure, and the airflow is sucked into the ore passage. In the
third and fourth levels, the wind pressure difference is positive, indicating that the falling ore pushes the airflow out of the ore pass wellhead. As can be seen from the simulated wind speed vector in Figure 2, the direction of the wind flow in the ore pass in the experiment is the same as that in the numerical simulation. Comparing Figures 5 and 3, it is found that when the unloading flow is the same, the variation law of the airflow at the ore pass in the experiment is basically the same as that in the numerical simulation. The maximum wind current appears in the fourth level, and the wind current value appears in the third level.

2.2.2. Study on the Control of Ore Pass Dust by Unloading Interval. Through numerical simulation analysis, it can be seen that the unloading time interval of 6 s can avoid the superposition of impulsive airflow. It takes a certain time for the dust to settle after the dust is generated. To study the dust accumulation situation, two unloading experiments were carried out at intervals of 30, 60, and 90 s. The variation of the dust concentration of the breathing zone set in the fourth level is monitored (the measuring point is a), and the experimental test results are shown in Figure 7.

It can be seen from Figure 7 that the maximum dust concentration of the fourth level of the ore pass is 325 mg/m³ when the single unloading quantity is 4000 kg, and the dust is maintained at the highest concentration for 1 min. When the second unloading time is delayed by 30 s, the maximum dust concentration is superimposed at 2/3 min, and the highest concentration is 360 mg/m³. When the second unloading time is delayed by 60 or 90 s, the superimposed value of the dust concentration of the ore pass is gradually reduced. The dust concentration is no longer superimposed when the interval is 90 s. Therefore, to prevent superposition of dust concentration of continuous unloading dust, the unloading interval is maintained for at least 90 s.

2.2.3. Study on the Effect of Foam Dust Removal on the Dust Treatment of Unloading. To further reduce the dust produced by unloading and prevent dust entering the roadway polluting the environment, the foam dust removal technology is introduced to control the dust in the mine bunker. In the early stage, based on an orthogonal experiment, a foam formulation containing AOS (0.15%), AES (0.20%), BS-12 (0.05%), and CMEA (0.05%) was prepared to establish a foaming system in the ore pass. The system is shown in Figure 8. The overall foaming system is relatively simple, the key equipment is the foamer, and the foaming principle of the new foamer design is shown in Figure 9.

To study the relationship between the amount of foam and the water ratio increases. When the gas flow rate is shown in Figure 10. The foaming speed increases as the gas–water flow rate increases. When the gas flow rate reaches 30 m³/h, the foaming speed increases first and then tends to be stable with the increase of the water flow rate. When the air pressure is constant, the foaming rate decreases as the gas–water ratio increases; when the water pressure is constant, the foaming rate increases as the gas–water ratio increases. According to the analysis data, when the gas flow rate is 30 m³/h, the water flow rate is 15–20 L/min, and the optimum gas–water ratio is 3:1, and the foaming agent has the best foaming effect. In the above study, on the basis of the optimum foaming gas–water ratio of 3:1, the amount of foam in the ore pass is studied (the heights of the foams in the mine bunker are 0, 5, 10, 15, 20 cm). When the foams of different heights are added to the mine bunker, changes occurred in the dust.
concentration in the third and fourth levels after unloading, as shown in Figure 11.

After the unloading experiment was carried out by filling foams with different heights in the mine bunker, it was found that the dust concentration in the wellhead gradually decreased as the foam height in the mine bunker increased. However, the foam in the mine bunker mainly controls the dust at the bottom of the mine bunker. The increase in the foam height

Figure 4. Superposition of wind speed under different ore movement states.
Through this research, the following conclusions are drawn: other. The focus of our future research will be the combined unloading time interval and foam dust removal are studied in the mine bunker can control 60% of the dust in the fourth level and up to 30% of the dust in the third level.

3. CONCLUSIONS

The unloading time interval and foam dust removal are studied in this paper. Obviously, dust pollution at all levels affects each other. The focus of our future research will be the combined automatic dust reduction in different layers of the ore pass. Through this research, the following conclusions are drawn:

(1). In the ore pass, the impinging airflow generated by unloading is key to dust pollution. It is known that the third and fourth levels have impinging wind currents, and the fourth level wind speed can reach about 2.0 m/s in the ore pass. The third and fourth levels are the main dust-producing points when the first level is unloaded. When the unloading flow rate is constant, the unloading weight is directly proportional to the unloading airflow.

(2). When the unloading quantity is 4000 kg with at least a 90 s interval two times, the concentration of continuous unloading dust will not be superimposed. It is necessary to ensure that the adjacent unloading interval is greater than 90 s at the actual unloading, avoiding the superposition of dust concentration.

(3). To control the dust pollution of the ore pass unloading, the optimum gas–water ratio of the dust-removing foam formulation was determined to be 31 (0.15% AOS, 0.20% AES, 0.05% BS-12, and 0.05% CMEA). Through the study of the relationship between the foam height and the dustfall rate in the mine bunker, it is found that the optimal dust control effect can be achieved when the foam height in the mine bunker is 15 cm.

4. COMPUTATIONAL METHODS AND EXPERIMENTAL SECTION

4.1. CFD—DEM Model Establishment. Since dust is carried by the impinging airflow in the ore pass, the impinging airflow is key to the dust diffusion in the ore pass, and it is very important to study the impinging airflow generated by the unloading. According to the field experience, the two factors of single unloading quantity and unloading interval during continuous unloading have a great influence on the impinging airflow. The impinging airflow is essentially the relative motion between the particles and the gas, that is, the process by which the ore gravitational potential energy is converted into air kinetic energy. Yu et al.25 and Lei et al.26 used the open source advantages of CFD to edit the API interface and realize the data transfer between EDEM and Fluent. In this paper, the influence of the impact of airflow in the ore pass and the distribution law of the impinging air is studied in the same way.

4.1.1. Mathematical Models of Gas—Solid Flow. For the analysis of the gas–solid two-phase flow problem in unloading, the following two assumptions are generally made: air ideally at a constant temperature is a continuous, incompressible medium; and the relative movement between the ore and the air enables energy exchange.27–30 The mathematical model was established to theoretically analyze the dynamic changes of the impinging airflow during the falling of the ore in the ore pass. The gas mass and momentum conservation continuity control equation can be expressed as

\[
\frac{\partial (\epsilon_g \rho_g \bar{U}_g)}{\partial t} = -\nabla (\epsilon_g \rho_g \bar{U}_g) + \frac{\partial}{\partial t} \left[ \epsilon_g \rho_g \bar{U}_g \otimes \bar{U}_g \right] + \nabla \left( \epsilon_g \mu \nabla \bar{U}_g \right) - \epsilon_g \rho_g g - \sum F_{\text{drag}}
\]

where \( \epsilon_g \) is the fluid volume fraction, \( \rho_g \) is the density of the fluid, \( t \) is time, and \( \bar{U}_g \) is the velocity of the fluid.

Equations of ore particle motion can be written as

\[
\frac{m_p d \bar{U}_p}{dt} = F_p + F_{\text{saff}} + F_{\text{drag}} + F_{\text{mag}} + F_{\text{p-p}} + F_{\text{p-w}}
\]

where \( m_p \) is the mass of the particle, \( \bar{U}_p \) is the linear velocity of the ore particle, \( F_p = m_g \) is the force of gravity of the ore particle, \( F_{\text{saff}} \) is the Saffman lift force, \( F_{\text{mag}} \) is the Magnus lift force due to particle rotation, \( F_{\text{p-p}} \) is the ore particle–ore particle collision force, and \( F_{\text{p-w}} \) is the ore particle–ore pass
The force applied to the ore in the ore pass is analyzed by the CFD–discrete element method (DEM) coupling software, as shown in Figure 12.

4.1.2. Establishment of a Geometrical Model. Taking the ore pass of the Anhui Mining Group iron mine as an example, a three-dimensional pass analysis model is established. The ore pass is 90 m high, transporting four levels of ore. The stratification height of each ore pass is 20 m, the diameter of the ore pass is 3.5 m, the diameter of the mine bunker is 5 m, the diameter of the ramp is 3.0 m, and the angle between the ramp and the ore pass is 35°. Directly connected to the ramp, the crosscut is 15 m long, 4 m wide, and 4.5 m high. The

Figure 7. Variation of dust concentration in the fourth level under different unloading time intervals.

Figure 8. Schematic diagram of the experimental apparatus of foam generation.
model establishment and meshing are shown in Figure 13. To study the influence of the single unloading amount on the impinging airflow in the ore pass, single unloading amounts $Q = 2000, 3000, 4000, 5000$, and $6000$ kg are used on the basis of $4000$ kg for the simulation analysis. To study the influence of the unloading interval on the impinging gas flow during continuous unloading, the two consecutive unloading intervals are $1, 2, 3, 4$, and $6$ s for the simulation analysis, when the constant single unloading quantity is $3000$ kg. The ore pass has four levels. When unloading at the first level, assuming that the air flow direction of each level is unknown, the first level is set as the pressure inlet and the rest of the levels are set as the pressure outlet. The pressure values of different middle sections are set according to the height drop. The setting of calculation model boundary conditions is shown in Table 2.

4.2. Establishment of the Ore Pass Experiment Platform. It is difficult to establish a $1:1$ experimental model because the size of the ore pass is large. To ensure the feasibility of the experiment, similar criteria were used to scale the original size, and a similar experimental model of the ore pass was established to conduct scientific research.
The ore pass unloading dust analysis experimental platform mainly consists of four parts: the ore pass model, the unloading device, the microcomputer laser dust monitor (model: LD-5C), and the multiparameter wind speed monitor (model: JFY-4), for real-time monitoring and recording of the unloading process and parameters. According to the similarity criterion of the ore pass model, the similar model size to the actual size ratio is 1:25, which can meet the geometric similarity. The similarity model of the ore pass is 3.6 m high. The stratification height of each ore pass is 0.8 m, the diameter of the ore pass is 0.14 m, the diameter of the mine bunker is 0.2 m, the diameter of the ramp is 0.12 m, and the angle between the ramp and the ore pass is 35°. Directly connected to the ramp, the crosscut is 0.6 m long, 0.16 m wide, and 0.18 m high. To visualize the analysis of the generation and migration of dust in the ore pass during the ore drop process more clearly, an ore pass experimental model is established using high-strength, high-pressure acrylic materials. The established slide unloading experimental platform is shown in Figure 14. The A−D marked on the model is the differential pressure measuring point. The positive and negative pressure differences reflect the direction of the airflow in the ore pass; a is the monitoring point of the dust concentration, the wind speed, and the dust particle size change. After the experiment, the unloading quantity follows similar criteria, the single unloading quantity is 1.28 kg, and the unloading flow rate is 0.64 kg/s.

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![Figure 13. Generation of the model meshes.](image)

![Figure 14. Similar experimental platform for ore unloading.](image)

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| Table 2. CFD–DEM Software Coupling Analysis Parameter Setting |
|-------------------------------------------------------------|
| **name**          | **parameter setting** | **name**          | **parameter setting** |
| Fluent solver type | pressure-based        | Fluent save data file every (time steps) | 3 |
| time transient    | 9.81 m/s²             | Fluent max iterations/time step | 0.3 |
| gravity           | gradient change       | Fluent solution method scheme (SIMPLE) |
| pressure inlet/outlet | Hertz–Mindlin model  | Fluent particle density | 4800 kg/m³ |
| EDEM particle contact model | particle radius | 0.05−0.1 m |
| EDEM wall no slip | unloading speed | 2000 kg/s |
| wall distribution | R–R |

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Notes
The authors declare no competing financial interest.

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