Numerical Simulation of the Dust Production and Transportation Law of an Intermediate Mine Heap

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ABSTRACT: In view of the current serious dust generation and environmental pollution that occur during the unloading process of an intermediate mine heap, in this study, the flow field and dust migration law for an intermediate mine heap were simulated numerically. Based on the mathematical model of the flow field and dust field, a numerical simulation was used to obtain the impact airflow and dust distribution law under different unloading conditions. The effects of different factors on the impact airflow and dust were studied. It could be concluded that the maximum impact wind velocity and dust concentration increased with an increase in the unloading flow. When the heap height is 23 m, the relationship between the maximum impact wind velocity and unloading volume was $v = 0.05124(M)_{(0.62584)}$ and the relationship between the dust concentration and mine unloading flow was $c = 7.05613(M)_{0.35002}$. The smaller the ore particle size, the larger the impact airflow and the greater the dust concentration. The relationship between the maximum impact wind velocity and the particle size was $v = 1.54000(d)^{-0.23786}$. The relationship between the dust concentration and ore particle size was $c = 30.45323(d)^{-0.54273}$. The greater the maximum impact wind speed, the more the dust generated. The existence of natural wind flow will initially accelerate the speed of dust diffusion and increase the dust concentration, but with the increase in natural wind flow, the diffusion effect will gradually reduce the dust concentration. An increase in the mine heap height will cause the impact wind’s speed and influence range to continuously decrease but will only have a small effect on the dust concentration.

1. INTRODUCTION

With the rapid development of China’s economy, China’s demand for minerals is increasing.1 In 2018, China’s copper mine output was 1.6 million tons. The increase in production capacity has caused the dust produced to become more and more serious, which is harmful to human health and the environment.2–4 An intermediate mine is a place for regulating mining transportation in metal mines. Because an intermediate mine heap displays a height difference when unloading, a large amount of dust is generated. This is particularly serious when the height difference is large. It severely pollutes the operating environment and affects the operating area and the health of workers.

The generation of dust is affected by a variety of factors. Evans et al.5 studied the effects of the material characteristics, moisture content, particle size distribution, material mass flow, and drop height on dust production. Wypych6 discovered that the temperature of the material has an important effect on dust production. The migration, diffusion, and distribution characteristics of dust in an intermediate mine heap belong to the research scope of gas–solid two-phase flow.7 The numerical simulation of gas–solid two-phase flow mainly includes two methods: the Euler–Lagrangian method and Euler–Euler method. The former is solved in the Euler coordinate system for the fluid phase, while the granular phase is solved in the Lagrange coordinate system; the latter is solved in the Euler coordinate system for both phases.8–11 The group of particles is regarded as a continuous medium. Additionally, the dust-containing gas stream is regarded as a “two-phase flow” in which the gas phase and the particle phase are mutually coupled. Reeks,13 James,14 and Arpa15 et al. conducted theoretical studies on the gas–solid two-phase flow viscosity near a wall. Zhang16 and Cui17 discussed the effects of gravity and static electricity on particle diffusion and gave theoretical calculation expressions. Noorani et al.18 studied the effect of the turbulence of gas–solid two-phase flow in a tube on large particle suspension. Colle19 studied the relationship between the dust concentration and wind velocity in wind flow. He proposed the minimum wind velocity required to exhaust the dust concentration. Alam20 studied the diffusion and dispersion of dust during rock drilling in wells and lanes and gave one-dimensional and two-dimensional equations.
for dust diffusion. Wang et al.\textsuperscript{21,22} established a mathematical model of the surface roughness of X-type swirl pressure nozzles. They studied the effect of the swirling exhaust ventilation ratio of the Coanda wall on the mechanized mining face during dust control. American scholar Wang\textsuperscript{23} carried out gas−solid two-phase flow experiments and concluded that the velocity of dust movement in the boundary layer is greater than the gas velocity. Hodkinson\textsuperscript{24} experimentally studied the mixing of respirable dust in the airflow in a fully mechanized mining face. Through an experiment of dust dispersion in the working space, the distribution curve was drawn based on the measured data. The change in dust concentration in the wind direction under the experimental conditions was obtained. The rule is that the dust concentration is generally 10−20 m from the downwind direction of the shearer. Ansart, Letourneau, Ansart et al.\textsuperscript{25,26} studied the dispersion behavior of a particle jet and the dust generation mechanism through an experiment and particle image velocimetry technology. Through a study of the particle flow, the particle size, drop height, mass flow rate, and particle stream diffusion relationships were obtained. Zhou et al.\textsuperscript{27−31} studied the inhibitory effect of multinozzle atomization, highwater absorption fire-extinguishing gel, a dust suppression binder, an environmentally friendly agglomerant, and an anionic surfactant on coal dust in a hydraulic support. Xiu et al.\textsuperscript{32} proposed a method of compressed air shunt ventilation by simulating the law of dust movement and distribution for a roadway during “long pressure short pumping”-type dust removal ventilation. Nie et al.\textsuperscript{33−36} simulated the ventilation system of the mine tunnel and proposed relevant measures to suppress dust. A lot of research has been done on the production and transportation mechanism of mine dust. However, research on the law of dust generation and transportation during the unloading process of intermediate mine heaps is still lacking. At present, most of the research studies on the dust pollution from the unloading of the intermediate mine piles focus on the actual engineering and technical measures, and there are few research studies on the dust generation points, distribution characteristics, and migration laws of dust. The current dust control measures mainly include spray dust reduction, airtight dust removal, and so forth. However, because of the complex operating environment and large air currents, the dust concentration is still high. Therefore, in-depth research in theory and control measures is required.

This study takes a copper mine intermediate mine heap as the research object and establishes a mathematical model of the flow field and dust field for the unloading process. The effect of the concentration and the simulation results were fitted to obtain the dust production law. At the same time, this study studies the various factors that affect the impact wind speed. The research results can provide a reference for the dust control of intermediate mine heaps.

2. RESULTS AND DISCUSSION

2.1. Numerical Simulation Results and Analysis of the Flow Field under Different Boundary Conditions.

2.1.1. Spatiotemporal Distribution Characteristics of the

![Figure 1. Distribution of ore particles during unloading.](image1)

![Figure 2. Merry current vector diagram of x = 0 and y = 0 sections.](image2)
Figure 3. Variation in the horizontal wind velocity at different mine unloading flows. (e) Variation in the maximum impact wind velocity with unloading flow.
Flow Field in the Heap Unloading Process. The simulated boundary condition unloading flow rate was set to 1000 kg/s; heap height was set to 23 m; natural wind velocity was set to 0 m/s; and unloading time was set to 10 s. The ore drop distribution of the intermediate mine heap was obtained through numerical simulation (see Figure 1). It can be known that during the ore dropping process, large-sized ore is mainly distributed in the central region of the mine flow, while small-sized ore particles are mainly distributed at the edges and gradually spread out. This is because the speed of the ore particles is different from that of surrounding air during the unloading process. Additionally, relative movement occurs.
between the ore and air and forms frictional resistance. The particle spacing inside the ore particle flow is small, and the frictional resistance is uneven. Because of the difference in resistance between the two sides of the particle, an outward shear force is generated, so the ore particle flow will have a tendency to rotate outward. When the air resistance reaches a certain value, the ore particles will rotate and escape from the particle flow. This phenomenon is particularly obvious for particles with smaller sizes. Therefore, as the ore flow drops, the large-size ore gathers in the core area of the ore flow, while the small-size ore continues to spread outward as the height of the ore flow increases.

Figure 2 is a wind current vector diagram of the flow field in the unloading area at different times.

It can be seen from Figure 2 that as the ore starts unloading, a vortex rotating from the inside to the outside is formed around the ore falling path. As the unloading time increases, the vortex continues to expand downward and outward. After the end of unloading, the vortex still exists and the gas in the unloading area still moves from the inside to the outside.

2.1.2. Impact of Different Unloading Flows on the Impact Airflow. The simulation was carried out for the following parameter settings: unloading flow $M_p$ of 500, 1000, 1500, and 2000 kg/s; heap height of 23 m; and unloading time of 10 s (see Figure 3). From Figure 3a−d, it can be seen that from the beginning of unloading to the end of unloading, the impact wind velocity at different heights increases with time and it first increases sharply and then stabilizes. After the unloading, the impact wind velocity decreases sharply to a certain speed and then begins to slowly decrease. When comparing the data from Figure 3a−d, it can be seen that the larger the mine unloading flow, the greater the impact wind velocity; the magnitude of the impact wind velocity increases first and then decreases as the mine drop height increases. The curve of the maximum impact wind velocity obtained by fitting is shown in Figure 3e. At the same height level, the maximum impact wind velocity increases with the increase in the mine drop height.
unloading flow, but the increase trend is decreasing. The main reason for this is that the increase in unloading flow increases the interaction between the ore flow and the air, so the maximum impact wind velocity increases continuously. However, the increase in the maximum impact wind velocity slows down. This is because when the unloading flow increases, the degree of mine stream looseness is reduced and the contact between the ore particles inside the mine stream and the air is reduced. There is an approximate power function relationship between the maximum impact wind velocity and the unloading flow. The power exponent range of the function between the two is 0.07268–0.62584.

2.1.3. Impact of Different Ore Particle Sizes on Impact Airflow. This study simulated the unloading process with an average ore size of 0.05, 0.1, 0.2, and 0.3 m; unloading flow of 1000 kg/s; heap height of 23 m; and unloading time of 10 s. Figure 4 is the relationship between the maximum impact wind velocity and the ore particle size obtained with the unloading flow of 1000 kg/s. The smaller the ore particle size, the greater the impact wind velocity. This is because under the same conditions of heap weight, the smaller the ore particle size, the larger the specific surface area, the larger the area of interaction between the ore flow and the air, and the greater the impact airflow. Therefore, with the same unloading flow, the smaller the ore particle size, the greater the impact wind velocity. Under the condition of a constant ore unloading flow, the maximum impact wind velocity decreases with the increase in the ore particle size. The relationship between the maximum impact wind velocity and the ore size is an approximate power function (see Figure 4e). The power exponent range is approximately 0.43783 to 0.2378. Therefore, it can be seen that the relationship between the maximum impact wind velocity and the ore particle size is relatively stable. Based on the fitting function between the maximum impact wind velocity and the ore particle size, it can be seen that the maximum impact wind velocity decreases sharply with the increase in the ore particle size, but the decline rate continues to slow down. This is because as the particle size of the ore increases, the specific surface area of the ore decreases and the area of interaction between the ore stream and the air tends to decrease. The increase in the looseness of the ore flow will increase the interaction area between the ore flow and the air. However, the specific surface area changes more obviously. Therefore, as the ore particle size increases, the maximum impact wind velocity keeps decreasing but its decline trend slows down.

2.1.4. Impact of Different Natural Wind Velocities on Impact Airflow. This study simulated the unloading process with a natural airflow velocity of 0, 2, 4, and 6 m/s; unloading flow of 1000 kg/s; heap height of 23 m; and unloading time of 10 s. Figure 5 is the relationship between the maximum impact wind velocity and the time for different heights on the monitoring surface under different natural wind velocity conditions. The natural wind velocity 4 m/s was selected for further analysis. From Figure 5a, it can be seen that the wind velocity is different at different heights in the unloading area. After unloading is completed, the impact wind velocity of each height monitoring surface increases with the decrease in the height and remains relatively stable. In the unloading process, with the increase in the unloading time, the wind velocity of each horizontal level decreases rapidly.

As shown in Figure 5b, when the natural wind velocity is 4 m/s, the average impact wind velocity at the monitoring surface of Z = 30 m displays the smallest change. The monitoring surface was selected to analyze the relationship between the average impact wind velocity and different natural wind velocities. It can be seen from the figure that not only are the impact wind velocity changes at different horizontal levels significantly different (see Figure 5a) but also are the average impact wind velocity changes at the same horizontal level, under different natural wind conditions (see Figure 5b). At the Z = 30 m level, when the natural wind velocity is 0 m/s, the maximum impact wind velocity generated by the ore drop can reach 3.91 m/s. When the natural wind velocity is 2 m/s, because the direction between the impact airflow caused by the ore drop and the natural wind flow is different, the interaction between the two reduces the impact airflow. Therefore, the maximum wind velocity is only 2.42 m/s. When the natural airflow speed is 4 m/s, the natural airflow is dominant, and the impact airflow is insufficient to affect the overall direction of natural wind. According to the average wind velocity change of the Z = 30 m monitoring surface under different natural wind velocity conditions, the relationship between the natural wind velocity and the overall wind velocity in the unloading area was obtained (see Figure 5c). It can be seen from Figure 5c that when the natural wind velocity increases to 3.06 m/s, the wind velocity in the unloading area displays the smallest change (0 m/s), but the direction of the wind velocity has changed from a positive value to a negative value.

2.1.5. Impact of Different Mine Heap Heights on Impact Airflow. This study simulated the ore unloading process with a heap height of H = 15, H = 20, and H = 25 m; unloading flow of 1000 kg/s; and unloading time of 10 s. The simulation results are shown in Figure 6. The changes in the average wind velocity at the Z = 30 m level in the different mine heap heights were compared. The results indicate that as the mine heap height increases, the impact wind velocity keeps decreasing and the decreasing range is increasing. During the increase in the heap height from 15 to 20 m, the maximum value of the average wind velocity at the Z = 30 m level decreased by 0.15 m/s. However, for the Z = 30 m horizontal surface, with the increase in the mine heap height from 20 to 25 m, the maximum average wind velocity decreased by 0.53 m/s. It shows that with the increase in the height of the mine heap, the airflow velocity at each point in the ore unloading area continues to decrease. This proves that the existence of a heap not only has a greater impact on the airflow nearby but also affects the flow field in the entire unloading area.
2.2. Numerical Simulation Results and Analysis of Dust Movement during Unloading.

2.2.1. Spatial and Temporal Distribution of Dust Movement in the Unloading Process of an Intermediate Mine Heap.

The ore unloading process simulation was carried out with the unloading flow of 1000 kg/s, unloading time of 10 s; heap height of 23 m; and natural airflow velocity of 0 m/s. The results are shown in Figure 7. At different heights of the same vertical section, the dust concentration increases with the ore drop height. The dust concentration and maximum value of the dust concentration both show an increasing trend. Meanwhile, when comparing Figure 7a with 7b, it can be seen that the dust concentration does not show the same trend. Because the ore has a certain initial velocity, the dust concentration of $X = -7$ m is greater than that of $X = 7$ m. With the decrease in heap height, the difference of the dust concentration among the four sections decreases gradually. When $Z = 24$ m, the dust concentrations in the positive and negative x direction are almost the same, indicating that the influence of the initial velocity at $Z = 24$ m has already become small. The change trends of dust concentration on both monitoring surfaces $Y = 6$ m and $Y = -6$ m are basically the same. This is because the ore flow is symmetrical along the X axis, and the impacts of the ore airflow and dust dissipation are also symmetrical along the X axis.

Comparing Figure 3, it can be found that the time required for the maximum dust concentration to reach the maximum value is longer than the time required for the impact airflow to reach the maximum value. The dust concentration only reaches the maximum value after the unloading is completed. This is because the unloading area is relatively open, and in the absence of natural airflow, the dust is only affected by the impact airflow and the diffusion speed is slow. However, the dust continuously escapes from the ore flow, so the dust is continuously accumulated in the unloading area, and the dust concentration is continuously increased until unloading is finished. When comparing the dust concentration at different heights of the same monitoring section, it can be seen that as the drop height of the ore increases, the dust concentration continues to increase. There are two main reasons for this phenomenon. One reason is that with the increase in the height of the ore, the looseness of the ore flow increases. Then, the impact airflow continues to increase, the dust effuses more seriously, and the dust concentration gradually increases. The other reason is that after unloading onto the heap, the dust deposited on the mine heap is raised to form secondary dust.

Figure 7. Changes in the average dust concentration at different heights of the section over time when the unloading flow $M_p = 1000$ kg/s.
2.2.2. Influence of Different Ore Unloading Flows on the Dust Concentration. This study simulated the unloading process with an unloading flow of 500, 1000, 1500, and 2000 kg/s; heap height of 23 m; unloading time of 10 s; and natural wind velocity of 0 m/s. Figure 8 exhibits the changes in dust concentration with different unloading flows. As can be seen in Figure 8a, as the ore unloading flow increases, the dust concentration at the top of the intermediate mine heap continues to increase. However, when the dust concentration reaches the maximum value, the decline rate is faster. It can be seen that the magnitude of the ore unloading flow has a large effect on the peak dust concentration but has a small effect on the duration of the dust concentration. The relationship between the maximum value of the dust concentration and the unloading flow under different flow conditions was fitted as $c = 7.05613(M_p)^{0.35002}$, as shown in Figure 8b.

2.2.3. Effect of Different Ore Particle Sizes on the Dust Concentration. The ore unloading process was simulated with an average ore particle size of 0.05, 0.1, 0.2, and 0.3 m; ore unloading flow of 1000 kg/s; mine heap height of 23 m; and ore unloading time of 10 s. As can be seen in Figure 9a, the dust concentration at the top of the mine heap decreases with the increase in the ore particle size. This is because the smaller the ore particles, the greater the impact airflow, and the proportion of fine ore particles increases. The combination of these factors led to a continuous increase in the dust concentration in the unloading area as the particle size of the ore decreased. The relationship between the maximum dust concentration at the top of the mine heap and the particle size of the ore was fitted as $c = 30.45323d^{-0.54273}$, as shown in Figure 9b.

2.2.4. Influence of Different Natural Wind Velocities on the Dust Concentration. This study simulated the unloading process with a natural wind velocity of 0, 2, 4, and 6 m/s; unloading flow of 1000 kg/s; mine heap height of 23 m; and unloading time of 10 s. The simulation results are shown in Figures 12 and 13. Because of the existence of natural wind, the dust distribution in the intermediate mine heap changed dramatically. The dust in the unloading area was no longer only affected by the impact wind velocity caused by the falling of the ore. Instead, it was also affected by the horizontal natural wind flow. With the increase in the natural wind velocity, the rising and falling rate of the dust concentration on each monitoring surface increases. Moreover, the time required to reach the maximum value of the respective dust concentration decreases continuously. At the same time, the maximum value of the dust concentration of each monitoring surface also decreases. With the increase in the distance from the ore unloading mouth, the maximum value of the dust concentration continues to decrease, and at the same...
time, the rate of increase and decrease in the dust concentration also slows down. From Figure 10, it can be seen that in the $X = 20$ m section, the dust concentration rises from 4.85 s up to the maximum value of 110.5 mg/m$^3$ at 15.6 s and falls below 10 mg/m$^3$ at 24.75 s; in the $X = 30$ m section, the dust concentration rises from 10 s up to the maximum value of 49.93 mg/m$^3$ at 24.75 s and falls below 10 mg/m$^3$ at 41.6 s; and in the $X = 40$ m section, the dust concentration rises from 14.55 s up to the maximum value of 34.27 mg/m$^3$ at 31.25 s and falls below 10 mg/m$^3$ at 50.3 s. It can be seen that as the distance from the ore unloading mouth increases, the maximum value of the dust concentration continues to decrease. Furthermore, both the increase and decrease rates of the dust concentration also slow down.

Comparing the dust concentration in the $X = 20$ m section under different natural wind velocities (see Figure 11), it can be seen that when the horizontal natural airflow $v = 0$ m/s, the dust concentration in the $X = 20$ m section is almost 0. This is because there is no natural airflow. Dust is only affected by the impact airflow, and only a very small amount of dust can diffuse to the $X = 20$ m section. When there is a natural wind current, as the natural wind velocity increases, the peak value of the dust concentration continues to decrease and the time required to reach the peak value continues to advance. At the same time, it can be found that as the natural wind velocity increases, the duration of the peak dust concentration also increases. Therefore, under the same unloading conditions, the magnitude of the horizontal natural wind velocity has a large impact on the size of the dust concentration peak and the duration of the dust concentration peak. The maximum dust concentration in the $X = 20$ m section changes with the natural wind velocity. When the natural wind velocity is 0, 2, 4, and 6 m/s, respectively, the maximum dust concentration is 0.31, 110.50, 83.09, and 65.39 mg/m$^3$. It can be inferred that when the natural airflow speed is small, the natural airflow accelerates the diffusion of dust, so that the pollution range of the dust is enlarged, and the average dust concentration in the pollution area is still large. However, when the natural airflow speed becomes even larger, the diffusion effect is further enhanced, but at the same time, the average dust concentration in the contaminated area is also reduced.

2.2.5. Effect of Different Heap Heights on the Dust Concentration. The ore unloading process was simulated with a heap height of 15, 20, and 25 m; unloading flow of 1000 kg/s; natural wind speed of 0 m/s; and unloading time of 10 s. The results are shown in Figure 12. It can be seen that the change in the heap height has little effect on the peak value of the dust concentration at the top of the heap. However, it has a certain effect on the time required to reach the maximum value of the dust concentration. When the heap height $H = 15$ m, the dust concentration reaches its peak the fastest. This is because the height of the mine heap is lower, so the height difference for unloading is larger. As a result, the speed at which the ore falls to the mine heap is greater. This leads to a greater amount of deposited dust being impacted and more dust being lifted, which causes the dust concentration at the top of the heap to rise rapidly. However, when the heap heights are 20 and 25 m, the difference between the two dust concentration curves is small.

3. CONCLUSIONS

This study simulated the distribution of impact airflow and the dust production—transportation rule during heap unloading. The following conclusions can be drawn:

1. After the ore particles descend, a diffusion phenomenon will be formed. Large-size ore is mainly distributed in the central area of the ore flow, while small-size ore is mainly distributed on the edge and gradually spreads. The impact

Figure 10. Relationship between the flour dust concentration over time when the natural wind velocity is 2 m/s.

Figure 11. Dust concentration with time under different natural wind velocities in the $X = 20$ m section.

Figure 12. Dust concentration with time at the heap top for different heap heights.
wind velocity increases with the increase in the unloading flow rate. The relationship between the maximum impact wind velocity and the unloading volume is \( v = 0.05124(M_d)^{0.62584} \). Under the same unloading flow conditions, the smaller the ore particle size, the larger the impact wind velocity. The relationship between the maximum impact wind velocity and the ore particle size is \( v = 1.54400(d)^{-0.23786} \).

(2) With the increase in the natural wind velocity, the turbulence of the impact airflow becomes greater. The relationship between the change in wind velocity in the unloading area and the natural wind velocity is \( \Delta v = 8.40446 e^{(-v/4.808555)} \) \( - 4.44432 \). When the natural wind velocity is 3.06 m/s, the change in wind velocity in the unloading area is the smallest. The increase in the height of the mine heap will reduce the impact wind velocity at each point in the unloading area.

(3) Dust concentration is greatly affected by the discharge unloading flow. The relationship between the maximum dust concentration and the unloading flow is \( c = 7.05613(M_d)^{0.33002} \). The dust concentration decreases with the increase in ore particle size, and the relationship between the maximum dust concentration and the ore particle size is \( c = 30.45323(d)^{-0.54273} \). Therefore, the unloading flow should be reduced and the ore particle size should be increased properly.

(4) With the increase in natural airflow, the dust concentration first increases and then decreases. At \( X = 20 \) m, when the natural wind velocity is 0, 2, 4, and 6 m/s, the maximum dust concentration is 0.31, 110.50, 83.09, and 65.39 mg/m³, respectively. The change in the heap height has a certain effect on the time required to reach the maximum dust concentration. Therefore, the heap height should be kept at a relatively high position.

4. COMPUTATIONAL METHODS AND EXPERIMENTAL SECTION

4.1. Mathematical Model. 4.1.1. Mathematical Model of Air Flow in an Intermediate Mine Heap. In this study, the flow field is the turbulence for the unloading process. The current basic idea is to express the transient pulsation in a time-averaged equation through the k–ε two-equation model. Assuming that the fluid is an incompressible Newtonian fluid and ignoring the volume force, the three-dimensional incompressible and non-steady Navier–Stokes equation of the continuous-phase motion equation is (1)

\[
\frac{d}{dt} \rho_k = - \mathbf{F} + \rho_k \Delta \vec{v}_k
\]

(1)

Considering that the flow is incompressible, the continuous equation is (2)

\[
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0
\]

(2)

The momentum conservation equation is (3)

\[
\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_i u_j) = - \frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i - F_i
\]

(3)

where \( \rho_k \) is the density of the gas, \( \text{kg/m}^3 \); \( \tau_{ij} \) is the stress tensor; \( P \) is the pressure of the fluid phase, \( \text{Pa} \); \( G \) is the acceleration of gravity, \( \text{m/s}^2 \); \( x_i \) and \( x_j \) are coordinates in the \( x, y, \) and \( z \) directions, \( m; u_i \) and \( u_j \) are the velocity of the fluid in the \( x, y, \) and \( z \) directions, \( m/s; \) and \( F_i \) is the average particle fluid resistance of the control volume, N.

The k–ε turbulent flow energy equation is (4)

\[
\frac{\partial}{\partial t}(\rho_k \varepsilon) + \frac{\partial}{\partial x_j}(\rho_k \varepsilon u_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \frac{\varepsilon^2}{k} C_{t1} G_k - \frac{\varepsilon^2}{k} C_{t2} \rho_k + S_k
\]

(4)

where \( \mu_t = \rho_k C_{t1} \frac{k^2}{\varepsilon} \), \( G_k = \rho_k \frac{\partial}{\partial x_j} \left( \frac{\partial \varepsilon}{\partial x_j} \right) \); \( k \) is the turbulent kinetic energy; \( \varepsilon \) is the turbulent energy dissipation rate; and \( C_{t1}, C_{t2} \) are the turbulent energy terms; \( \mu_t \) is the turbulent viscosity coefficients, respectively, \( \text{Pa s}; \) \( \sigma_k \) and \( \sigma_{\varepsilon} \) are constants, with values 1.44, 1.92, 0.09, 1.3, and 1.0, respectively.

4.1.2. Mathematical Model of Dust Flow in an Intermediate Mine Heap. In the process of unloading, the volume of dust in the unloading area is less than 10%, and its density is far greater than that of air, so the volume of dust particles in the air can be ignored. Because the gravity, buoyancy, and air resistance of the dust particles are much larger than other forces, while ignoring the effects of other forces, a force analysis combined with Newton’s second law can be used to obtain the equation of motion of the dust. The equation of motion can be established as (5)

\[
\frac{d^2}{dt^2} \rho_i \frac{d\vec{v}_i}{dt} = \frac{\pi}{6} C_d d^2 \rho_i (\vec{v}_g - \vec{v}_i) \vec{v}_i - \vec{v}_g + \frac{\pi}{6} d^3 (\rho_d - \rho_g) g
\]

(5)

where \( d \) is the size of the dust particles, \( m; \rho_d \) is the density of the dust particles, \( \text{kg/m}^3; \) \( C_d \) is the aerodynamic drag coefficient; \( \vec{v}_g \) is the velocity of the gas, \( \text{m/s}; \) and \( \vec{v}_i \) is the velocity of the dust particles, \( \text{m/s}. \)

Dust particles collide by the random motion of gas molecules in the air. The dust diffusion from regions with a higher concentration to regions with a lower concentration due to Brownian motion is called Brownian diffusion. At the same time, because of the existence of fluid turbulence, dust diffusion occurs, which is called turbulent diffusion. In the process of unloading, both types of dust diffusion exist, and turbulent diffusion is the main factor influencing dust diffusion.

Because of the turbulent flow of the airflow, the amount of dust passing through a unit area along the \( x \) direction in a unit time is proportional to the dust concentration gradient in the \( x \) direction, which can be expressed as the following formula 6

\[
q_x = -K_x \frac{\partial c}{\partial x}
\]

(6)

where \( c \) is the dust concentration, \( \text{mg/m}^3; \) \( -\partial c/\partial x \) is the gradient of the dust concentration along the coordinate \( x \) direction; and \( K_x \) is the diffusion coefficient in the \( x \) direction.

Considering that both the area of the inlet and outlet in the \( x \) direction in the unit volume \( \Delta x \) is \( \Delta y \Delta z \), the turbulent diffusion process allows the dust to enter the small cube through two small aspects: \( \Delta y \Delta z \) at \( x \) and \( x + \Delta x \). The entering net inflow is.
net inflow in the $x$ direction: $\left[-K_x \frac{\partial c}{\partial x}\right]_x - \left[-K_x \frac{\partial c}{\partial x}\right]_{x+\Delta x} = \Delta y \Delta z$

The same can be obtained for the $y$ and $z$ directions. Because the net inflow amount is equal to the cumulative rate, it can get formula 7

$$\frac{\partial c}{\partial t} = K_x \frac{\partial^2 c}{\partial x^2} + K_y \frac{\partial^2 c}{\partial y^2} + K_z \frac{\partial^2 c}{\partial z^2}$$

In isotropic air, the diffusion coefficients of dust particles in the three directions of $x$, $y$, and $z$ are the same and can be expressed by $K_p$. The diffusion coefficient is a reflection of the ability of dust to diffuse in the air. Therefore, the dust with different particle sizes has different diffusion values.

When the particle diameter $d_p$ of the dust is equal to the mean free path of the gas molecules and also the Knudsen number $K_n = \frac{24}{d_p} \leq 0.5$, then, the diffusion coefficient $K_p$ of the dust can be obtained by Einstein’s formula, and the formula is (8)

$$K_p = \frac{4kT}{3\pi d_p^2} \sqrt{\frac{8RT}{\pi M}}$$

where $P$ is the pressure of the gas, Pa; $R$ is the gas constant, $\text{J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$; and $M$ is the molar mass of the gas, kg/mol.

By analyzing the relationship among the diffusion of dust particles, the sedimentation distance, and the particle size, it can be seen that dust particles smaller than $0.5 \mu m$ mainly diffuse and dust particles larger than $5 \mu m$ mainly fall.

**4.1.3. Particle Size Analysis of the Main Dust Sources.** The mine collected on the belt of the crushing station was transported to the laboratory for testing. For the particle size, 8.70% of the ore particles were greater than 2 mm, 52.36% were greater than 50 mm, and 8.61% were below 2 mm. Figure 13 is the Rosin–Rammler (R–R) distribution function of the ore particle size obtained by fitting.

The ore particle size distribution function of the intermediate mine heap of the L mine is (9)

$$G = 1 - \exp[-44.64802d^{0.91425}]$$

Figure 13. Rosin–Rammler function fitting curve of the ore particle size.

In order to ensure the reliability of the simulation results, the ore particle size distribution was arranged according to Figure 13 in the numerical simulation process.

**4.2. Establishment of the Geometric Model and Determination of the Parameters.**

(1) Geometric model and mesh division

Geometry modeling was performed using a copper mine’s intermediate heap operation site as a prototype. The overhead truss of the belt conveyor was 158.9 m long and 36 m high, at an angle of 13° from the horizontal section. The intermediate heap was a cone-shaped heap, the natural rest angle was 37°, and the maximum diameter was 90 m. The heap center was taken as the origin of the coordinates. The heap geometric model was established, as shown in Figure 14a. Then, the model was gridded through ICEM CFD (The Integrated Computer Engineering and Manufacturing Code for Computational Fluid Dynamics) software. Because the study objects were the wind flow and dust movement in the ore falling area, the relative area was gridded and encrypted. The grid independence was checked and the grid size was 300 mm. The mesh division result is shown in Figure 14b.

(2) Setting of boundary conditions

In this study, the time step is calculated by dividing the minimum grid length by the velocity of flow or the velocity of rotating flow. Such a result can ensure that each iteration is within a grid range without resulting in errors across the grid. The minimum size of the grid is 300 mm, the maximum characteristic flow rate is 10 m/s, the Courant number is 2, the calculated time step is 0.06 s, and the actual time step is 0.05 s.

Table 1 shows the boundary conditions based on the field investigation and related parameter calculation.

The particle size distribution of ore and dust is R–R distribution, but the distribution coefficient is different. According to the statistical analysis results, the maximum particle size of dust is 98 μm, the minimum particle size is 0.848 μm, the median diameter is 5.671 μm, and the distribution coefficient is 1.1. The maximum grain size of the ore was 300 mm, the minimum grain size was 2 mm, the median diameter was 53 mm, and the distribution coefficient was 0.91. The pressure boundary condition is standard atmospheric pressure.

**4.3. Model Verification of Numerical Simulation.** In this study, similar experiments are used to simulate the unloading process under the conditions of an unloading flow of 0.2, 0.4, 0.6, and 0.8 kg/s; mine heap height of 0.5 m; unloading time of 10 s; and natural wind flow of 0 m/s. Then, the change in dust...
concentration was tested, and the relationship between the maximum dust concentration and the unloading flow under different unloading flow conditions was fitted as \( c = 6.622 - (M_p)^{0.37348} \), which was close to the relationship between the unloading flow and dust concentration obtained by the numerical simulation \( c = 7.05613(M_p)^{0.35002} \), as shown in Figure 15, which verified the accuracy of the numerical simulation model.

Table 1. Boundary Condition Parameter Settings

| boundary condition | parameter setting | boundary condition | parameter setting |
|--------------------|------------------|--------------------|------------------|
| solver             | separation       | size distribution  | R−R distribution |
| turbulence model   | \( k−c \)        | particle size range | \( 8.48 \times 10^{-7} \) to 0.3 |
| inlet boundary type| velocity         | dust distribution index | 1.1 |
| exit boundary type | pressure         | ore distribution index | 0.91 |
| discrete phase model | open             | mass flow rate     | 500−2000 kg/s |
| resistance         | spherical        | turbulent diffusion model | random orbit model |
| jet source type    | surface jet      | discrete phase boundary | capture, bounce |
| material density (kg/m³) | copper ore | collision model | open |
| discrete format    | second order     | convergence criterion | \( 10^{-3} \) |

Figure 15. Verification of the relationship between the average dust concentration and discharge flow.

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### Notes

The authors declare no competing financial interest.

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### REFERENCES

1. Chen, J.; Chen, R.; Mao, Z.; Yang, H.; Zhang, C.; Han, R. Regional Mineral Resources Assessment Based on Rasterized Geochemical Data: A Case Study of Porphyry Copper Deposits In Manzhouli, China. Ore Geol. Rev. 2016, 74, 15−25.

2. Cui, D.; Baisheng, N.; Hua, Y.; Linchao, D.; Caihong, Z.; Fei, Z.; Hailong, L. Experimental research on optimization and coal dust suppression performance of magnetized surfactant solution. Procedia Eng. 2011, 26, 1314−1321.

3. Chen, R. H.; Wang, B. Q.; Wang, Z. B.; Yao, S. The pollution character analysis and risk assessment for metals in dust and PM10 around road from China. Biomed. Environ. Sci. 2015, 28, 44−56.

4. Sastry, V. R.; Chandar, K. R.; Nagesh, K. V.; Muralidhar, E.; Mohiuddin, M. S. Prediction and Analysis of Dust Dispersion from

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ACS Omega 2021, 6, 1623−1635
Drilling Operation in Opencast Coal Mines. *Procedia Earth Planet. Sci.* 2015, 11, 303−311.

(5) Evans, D. E.; Turkevich, L. A.; Roettgers, C. T.; Deye, G. J.; Baron, P. A. Dustiness of Fine and Nanoscale Powders. *Ann. Occup. Hyg.* 2013, 57, 261−277.

(6) Wypych, P.; Cook, D.; Cooper, P. Controlling Dust Emissions and Explosion Hazards in Powder Handling Plants. *Chem. Eng. Process.* 2005, 44, 323−326.

(7) Tan, C.; Jiang, Z.-A.; Chen, J.-S.; Wang, P. Numerical simulation of influencing factors for coal dust movement during comprehensive mining. *J. Univ. Sci. Technol. Beijing* 2014, 36, 716−721.

(8) Mashayek, F.; Pandya, R. V. R. Analytical dispersion of particle/droplet-laden turbulent flows. *Prog. Energy Combust. Sci.* 2003, 29, 329−378.

(9) Loth, E. Numerical Approaches for motion of dispersed particles, droplets and bubbles. *Prog. Energy Combust. Sci.* 2000, 26, 161−223.

(10) Minier, J.-P.; Peirano, E. The PDF approach to turbulent poly dispersed two-phase flows. *Phys. Rep.* 2001, 352, 1−214.

(11) Balachandar, S. A scaling analysis for point-particle approaches to turbulent multiphase flows. *Int. J. Multiphase Flow* 2009, 35, 801−810.

(12) Balachandar, S.; Eaton, J. K. Turbulent dispersed multiphase flow. *Annu. Rev. Fluid Mech.* 2010, 42, 111−133.

(13) Jin, C.; Potts, I.; Reeks, M. A simple stochastic quadrant model for the transport and deposition of particles in turbulent boundary layers. *Phys. Fluids* 2015, 27, 053305.

(14) James, P. W.; Wang, Y.; Azizpouradi, B. J.; Hughes, J. P. The Role of Drainage Channels in the Performance of Wave-Plate Mist Eliminators. *Chem. Eng. Res. Des.* 2003, 81, 639−648.

(15) Arpa, G.; Widiatmojo, A.; Widodo, N. P.; Sasaki, K. Tracer gas measurement and simulation of turbulent diffusion in mine ventilation airways. *J. Coal Sci. Eng.* 2008, 14, 523−529.

(16) Zhang, W.-F.; Lin, J.-Z. Research on the motion of particles in the turbulent pipe flow of fiber suspensions. *Appl. Math. Mech.* 2004, 25, 741−750.

(17) Cui, H.; Luo, F.; Wang, Z.; Dong, S. Simulation analysis of flow characteristics of Jatropha curcas oil in diesel injector. *Nongye Gongcheng Xuebao* 2013, 29, 63−71.

(18) Noorani, A.; Sardina, G.; Brandt, L.; Schlatter, P. Particle Velocity and Acceleration in Turbulent Bent Pipe Flows. *Flow, Turbul. Combust.* 2015, 95, 539−559.

(19) Colle, H. A.; Hiszem, K. J. Standing at a kiosk: Effects of key size and spacing on touch screen numeric keypad performance and user preference. *Ergonomics* 2004, 47, 1406−1423.

(20) Alam, S.; Mukhopadhyay, A. Diffusion of Gold Nanorods in Polymer Solutions. *Chin. J. Catal.* 2013, 34, 1861−1868.

(21) Wang, P.; Tian, C.; Liu, R.; Wang, J. Mathematical model for multivariate nonlinear prediction of SMD of X-type swirl pressure nozzles. *Process Saf. Environ. Prot.* 2019, 125, 228−237.

(22) Wang, P.; Li, Y.; Liu, B.; Shi, Y. Effect of forced-to-exhaust ratio of air volume on dust control of wall-attached swirling ventilation for mechanized excavation face. *Tunn. Undergr. Space Technol.* 2019, 90, 194−207.

(23) Wang, J.; Levy, E. K. Particle motions and distributions in turbulent boundary layers of air-particle flow a vertical flat plate. *Exp. Therm. Fluid Sci.* 2003, 27, 845−853.

(24) Erol, I.; Aydin, H.; Didari, V.; Ural, S. Pneumoconiosis and quartz content of respirable dusts in the coal mines in Zonguldak, Turkey. *Int. J. Coal Geol.* 2013, 116−117, 26−35.

(25) Ansart, R.; Letoumeau, J.-J.; de Ryck, A.; Dodds, J. A. Dust emission by powder handling: Influence of the hopper outlet on the dust plume. *Powder Technol.* 2011, 212, 418−424.

(26) Ansart, R.; Ryck, A. D.; Dodds, J. A. Dust Emission in Powder Handling: Free Falling Particle Plume Characterisation. *Chem. Eng. J.* 2009, 152, 415−420.

(27) Wang, J.; Zhou, G.; Wei, X.; Wang, S. Experimental characterization of multi-nozzle atomization interference for dust reduction between hydraulic supports at a fully mechanized coal mining face. *Environ. Sci. Pollut. Res.* 2019, 26, 10023−10036.