Analysis of the Influencing Factors of Discharge Port Blockage in the Funnel-Shaped Material Conveying Process

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Abstract

Material conveying is an indispensable process in mining production and processing. However, blockage at the discharge outlet during conveying seriously affects production efficiency. In this paper, the discrete element method is used to study the main factors affecting hopper blockage, including feeding rate, particle size, shape, and friction coefficient, with the hopper shapes set as straight, polygonal, curved, and reverse-curved types. The results show that when the feeding rate increases from 120 kg/s to above 150 kg/s, the blockage time occurs significantly earlier; particle size and shape significantly affect the blockage probability; and when the friction coefficient increases from 0.3 to 0.6, the blockage time occurs earlier. Comparison of hoppers with different shapes shows that the reverse-curved hopper performs well under high-speed feeding and has good anti-blockage capability for large particles and materials with high surface roughness. Its reverse-curved hopper wall structure can effectively conform to the sliding trajectories of particles and reduce collisions. The research results can provide a theoretical reference for improving material conveying efficiency in mining production and processing, and offer scientific guidance for the structural optimization design of hopper shapes.

Full Text

Analysis of the Influencing Factors of Discharge Port Blockage in the Funnel-Shaped Material Conveying Process

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Abstract: In the process of mining production and processing, material transportation is an indispensable process. However, the problem of blockage at the discharge port during the conveying process seriously affects production efficiency. In this paper, the discrete element method is adopted to study the main factors affecting funnel blockage, including feeding speed, material size, shape, and friction coefficient. The funnel shapes are set as straight type, polygonal type, curved type, and outer reverse-arc type. The results show that when the feeding speed increases from 120 kg/s to more than 150 kg/s, the clogging time point is significantly advanced; the particle size and shape of the material significantly affect the clogging probability; when the friction coefficient increases from 0.3 to 0.6, the clogging time point is advanced. By comparing funnels of different shapes, it is found that the outer reverse-arc funnel performs better at high feeding speeds; at the same time, it has better anti-clogging ability for large-particle materials and materials with high surface roughness. Its reverse-arc funnel wall structure can effectively conform to the downward sliding trajectory of particles and reduce collisions. The research results can provide theoretical reference for improving material conveying efficiency in mining production and processing, and offer scientific guidance for the structural optimization design of funnel shapes.

Keywords: material conveying; funnel shape; discharge port blockage; feeding speed; material shape

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Abstract: In the process of mining production and processing, material transportation is an indispensable process. However, the problem of blockage at the discharge port during the conveying process seriously affects the production efficiency. In this paper, the discrete element method is adopted to study the main factors affecting funnel blockage, including feeding speed, material size, shape, and friction coefficient. Among them, the funnel shapes are set as straight type, polygonal type, curved type, and outer reverse arc type. The results show that when the feeding rate increases from 120 kg/s to more than 150 kg/s, the clogging time point is significantly advanced. The particle size and shape of the material will significantly affect the

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probability of blockage. When the friction coefficient increases from 0.3 to 0.6, the clogging time point advances by 20%. By comparing funnels of different shapes, it is found that the outer reverse arc funnel performs well under high-speed feeding conditions. Meanwhile, it also has a better anti-clogging capability for materials with large particles and high surface roughness. Its parabolic funnel wall structure can effectively conform to the sliding trajectory of particles and reduce collisions. The above research results can provide theoretical reference for improving the material transportation efficiency in mining production and processing, and offer scientific guidance for the structural optimization design of funnel-shaped structures.

Key words: material transportation; funnel shape; discharge port blockage; feeding speed; material shape

In industrial production, continuous and efficient material transportation is a key link in ensuring the stable operation of production lines. The design of conveying structures needs to consider material convergence and diversion, hopper wear, belt deviation under receiving, dust raising, material scattering, energy saving, and efficiency optimization, etc.

$$1-5$$

. When materials arrive at the discharge port, the influence of aggregation and blockage inside the hopper on the conveying rate is very important. Blockage at the discharge port of material conveying systems has long plagued industries such as mining and chemical engineering

$$2,6-7$$

. According to statistics, downtime and maintenance time caused by poor discharge account for 15%-30% of the total failure time of production lines

$$8$$

, and blockage at the discharge port easily causes material accumulation and equipment wear, posing major safety hazards. Therefore, research on discharge-port blockage phenomena is of great significance.

Blockage is caused by the joint action of multiple factors. Physical experiments and PFC-CFD coupled numerical experiments have explored the microscopic mechanical mechanism of arch collapse and failure, pointing out that high-speed feeding may intensify the energy dissipation caused by collisions and maintain the local stability of the arch structure

$$9$$

. In addition, increasing the feeding speed in grain conveying systems can increase the fluctuation of grain flow and raise the blockage frequency [10], indicating that feeding speed is a key factor affecting the occurrence of blockage. Using the discrete element method to study the dynamic evolution process of arch structures when granular material flow passes through the hopper orifice shows that, at the initial stage of flow, a switching curve is formed between static particles and flowing particles, and an extremely small force-arch structure is generated below the switching curve, revealing the critical stress condition for blockage formation [11]. Physical properties such as particle shape, size distribution, and moisture content are internal factors that induce blockage. Studies on the transportation of shaped-particle materials show that an excessively large aspect ratio of particles makes them more likely to form interlocking structures at the hopper neck [12]; nonspherical particles such as prismatic particles are more likely than spherical particles to form flow obstruction [13]. Research on the motion characteristics of single spherical particles in transversely vibrating riser pipes has found that the ratio of particle diameter to pipe diameter is an important factor inducing collisions [14]. The distribution of asymmetric force-chain structures between particles during dynamic flow is the core mechanism inducing local blockage [15]. This indicates that material size and shape have an important influence on the occurrence of blockage. Material off-loading is also an important factor inducing blockage. Off-loading causes uneven distribution of materials in the width direction of the conveyor belt, producing transverse impact force and significantly increasing the transverse vibration amplitude of the conveyor belt and the tendency to deviate from the track [16–18]. Therefore, it is necessary to systematically study the related factors that lead to blockage during material transportation.

Experimental studies have found that conveyor-belt vibration can accelerate particle flow; therefore, blockage can be avoided by adding low-friction materials [19–20]

. Numerical analysis has determined the influence of hopper vibration-induced flow on the particle passing rate [21], and proposed a wall-based extensional shock-reducing and damping technology [22]. Based on fluid mechanics models, the flow states of materials in specific structures have been studied, thereby adjusting equipment parameters such as inclination angle and feeding speed [23]. In addition, the structural shape of the hopper also has a great influence on blockage. A bicurved hopper design can effectively improve flow uniformity [24]. The inclination angle of the hopper wall must be greater than the angle of repose of the material to ensure smooth flow; for viscous materials, the inclination angle needs to be further increased [25]. Therefore, optimizing the hopper shape can provide an effective scheme for avoiding, reducing, or delaying blockage.

Accordingly, this study uses the discrete element method to establish a numerical model of irregularly shaped materials, designs four hopper structures—straight, polygonal, arc, and reverse-arc—and analyzes the factors influencing discharge-port blockage. The numerical analysis process in this study is implemented using EDEM software.

1 Material Model and Structural Model of the Discharge-Port Hopper

To study the blockage phenomenon of materials at the discharge port during transportation, this study refers to the mining and production process of coal mines, establishes a discrete element model and conveying model for coal lumps, and analyzes the main factors affecting blockage.

1.1 Particle Model

Because the shapes of general coal lumps are irregular, this study establishes a discrete element model of materials with irregular shapes. Spherical units are used as the basic particles, and the numerical model of the material is established through bonding action [26–28]. The material particles and numerical model are shown in Fig. 1.

Fig. 1

Figure 1: Fig. 1

(a) Coal material (b) Particle numerical model

Fig. 1 Real coal particle and DEM model of coal particle

Because the coal on the conveyor belt is a bulk material, its shear resistance cannot be described by the shear modulus in traditional rigid-body mechanics. In this study, with reference to the experimental study by Gao Xia et al.

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on the correlation of mesoscopic mechanical parameters of coal bulk solids, the shear modulus was approximately estimated. The computational parameters of the material particles used in the simulation are listed in Table 1.

Table 1 Physical parameters of material particle

Tab. 1 Physical parameters of material particle

Parameter	Value
Shear modulus G/MPa	10
Poisson' s ratio ν	0.3
Coefficient of restitution e	0.3
Friction coefficient μ	0.5
Density $\rho/(\mathrm{kg}\cdot\mathrm{m}^{-3})$	1 600

In the process of open-pit mining production, the material before and after crushing is dominated by large coal lumps with relatively large particle size, while the proportion of small coal lumps is relatively low. According to the measured particle-size data of crushed coal in the underground workings of the Shuangyashan Shuangyang Coal Mine in Heilongjiang obtained by Gao Xia et al.

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, after neglecting extremely large particles that have an occasional influence on the study, the particle size of coal ore is concentrated in the range of 50–100 mm, i.e., the equivalent radius of a spherical element is approximately 17–33 mm. The measured coal-lump grading data for the 8103 fully mechanized caving face of the Shanxi Ruilong Coal Mine obtained by Zhang Jinwang et al.

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show that, after ignoring extremely small coal particles that essentially do not cause blockage, the proportion of coal particles increases approximately in an

Fig. 2

Figure 2: Fig. 2

Fig. 3

Figure 3: Fig. 3

arithmetic progression with increasing particle size

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. To make the simulation closer to actual production conditions, when studying influencing factors such as feeding speed, material shape, and friction coefficient, the proportion of large coal lumps was set higher than that of small coal lumps. The volume fractions of particles of different sizes are listed in Table 2, where r is the spherical-element radius and $r_0 = 18$ mm.

Table 2 Particle size distribution

Tab. 2 Particle size distribution

r/r_0	Proportion/%	r/r_0	Proportion/%
1	5	1.6	35
1.3	15	1.9	45

1.2 Funnel model

The converging effect of the funnel on particle flow is significant. To study the influence of funnel geometry on particle passing efficiency and blockage, four funnel structures were designed: straight, polygonal-line, arc, and reverse-arc. The numerical models of funnels with different geometries are shown in Fig. 2. In the reverse-arc funnel, the outer wall of the inlet part is composed of a circular-arc segment with constant curvature, similar to a parabolic design. Fig. 3 shows the established material-conveying model. The material parameters used for the numerical simulation of the conveying structure are listed in Table 3.

(a) Straight type (b) Polygonal-line type (c) Arc type (d) Reverse-arc type

Fig. 2 DEM models of funnels with varied geometries

Fig. 3 DEM model of material conveying

Table 3 Material parameters of the conveying structure in the simulation process

Tab. 3 Material parameters of the conveying structure in the simulation process

Parameter	Value
Shear modulus G/MPa	70
Poisson’ s ratio ν	0.3
Coefficient of restitution e	0.3
Friction coefficient μ	0.5
Density $\rho/(\mathrm{kg} \cdot \mathrm{m}^{-3})$	7 800

2 Calculation Method for Contact Force and Model Validation

2.1 Calculation Method for Contact Force

The discrete element method discretizes the system into independent particles/entities, and simulates the dynamic behavior of the system by calculating the contact forces between particles

$$31-32$$

. In the numerical simulation, an explicit integration method is adopted, and the positions and velocities of the particles are updated by solving Newton’ s equations of motion:

$$m_i \frac{\mathrm{d}v_i}{\mathrm{d}t} = \sum_{j=1}^{N} F_{ij} + F_{\mathrm{ext}} \qquad (1)$$

$$I_i \frac{\mathrm{d}\omega_i}{\mathrm{d}t} = \sum_{j=1}^{N} M_{ij} \qquad (2)$$

where m_i and I_i are the mass and moment of inertia of the particle, respectively; v_i and ω_i are the linear velocity and angular velocity of the particle, respectively; F_{ij} and M_{ij} are the contact force and moment between particles i and j, respectively; and F_{ext} is the external force. According to the specific working conditions, the Hertz-Mindlin model is selected in this study during the numerical simulation to calculate the contact forces between particle and particle and between particle and structure. Owing to particle deformation, the contact between two particles is not at a single point but over a finite region. This is equivalent in DEM to allowing two rigid bodies to have slight overlap. The distribution of the contact traction over this region can be decomposed into one component in the contact plane and one component perpendicular to the plane; therefore, the contact force has two components: normal and tangential

Fig. 4 Illustration of contact forces between particles

Figure 4: Fig. 4 Illustration of contact forces between particles

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Based on the Hertz-Mindlin model, the contact force between particle and particle is calculated. The schematic diagram of the interparticle contact force is shown in Fig. 4. The contact force includes the normal force and the tangential force. The normal force is

$$F_{\mathrm{n}} \propto E^{*}\sqrt{R^{*}}\,\delta_{\mathrm{n}}^{3/2} \qquad (3)$$

Fig. 4 Illustration of contact forces between particles

The specific proportionality coefficient is determined by integral derivation. Generally, the normal contact force is expressed as

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$$F_{\mathrm{n}} = \frac{4}{3}E^{*}\sqrt{R^{*}}\,\delta_{\mathrm{n}}^{3/2} \qquad (4)$$

where

$$E^{*} = \left(\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_1}\right)^{-1}$$

is the equivalent elastic modulus; E_1 and E_2 are the elastic moduli of the two particles, respectively; ν_1 and ν_2 are the Poisson' s ratios of the two particles, respectively; and

$$R^{*} = \left(\frac{1}{R_1} + \frac{1}{R_2}\right)^{-1}$$

is the equivalent radius, where R_1 and R_2 are the curvature radii of the two contacting particles at the contact point. To simulate collision energy loss, a damping term needs to be added to the normal contact force

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, namely

$$F_{\mathrm{n,damping}} = -\gamma_{\mathrm{n}} u_{\mathrm{n}} \qquad (5)$$

where γ_{n} is the normal damping coefficient, and u_{n} is the normal relative velocity. The total normal contact force obtained is

$$F_{\mathrm{n}}^{\mathrm{total}} = \frac{4}{3}E^{*}\sqrt{R^{*}}\,\delta_{\mathrm{n}}^{3/2} - \gamma_{\mathrm{n}}u_{\mathrm{n}} \qquad (6)$$

The calculation of the tangential contact force follows the incremental method

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. Considering the elastic deformation and friction between contact surfaces, the increment of tangential contact force can be expressed as

$$\Delta F_{\mathrm{t}} = -k_{\mathrm{t}}\Delta x \qquad (7)$$

where

$$k_{\mathrm{t}} = 8G^{*}\sqrt{R^{*}\delta_{\mathrm{n}}}$$

is the tangential stiffness; and

$$G^{*} = \left(\frac{2-\nu_1}{G_1} + \frac{2-\nu_2}{G_2}\right)^{-1}$$

is the equivalent shear modulus. G_1 and G_2 are the shear moduli of the two particles, respectively; ν_1 and ν_2 are the Poisson' s ratios of the two particles, respectively; and Δx is the relative displacement increment. To simulate tangential energy dissipation, tangential damping is introduced, namely

$$F_{\mathrm{t,damping}} = -\gamma_{\mathrm{t}}v_{\mathrm{t}} \qquad (8)$$

where γ_{t} is the tangential damping coefficient, and v_{t} is the tangential relative velocity

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. The tangential contact force obtained is

$$F_{\mathrm{t}} = -k_{\mathrm{t}}\delta_{\mathrm{t}} - \gamma_{\mathrm{t}}v_{\mathrm{t}} \qquad (9)$$

where δ_{t} is the interparticle tangential overlap. The calculation of the interaction force between nonspherical particles is likewise based on the above principles

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When solving the contact force between particles and the structure, the structure is treated as a sphere with an infinite radius

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2.2 Model Validation

To verify the correctness of the established model, the numerical simulation process of material accumulation and discharge was compared with the experimental results. In the numerical simulation, the contact force calculation model in Section 2.1 was selected to calculate the contact forces between particle and particle and between particle and structure, thereby simulating the dynamic behavior of the system. The positions and velocities of the particles were updated by solving Newton’ s equations of motion until the simulation process ended. The parameters used in the calculation are listed in Table 4. The material diameter was randomly distributed between 3.3 and 10 cm. The initial accumulation condition is shown in Fig. 5. The accumulation heights of the materials in the numerical simulation and experiment were both 9.3 cm. The variations of the wall slope angle α of the hopper during discharge with time in the experiment and numerical simulation are shown in Fig. 6. It can be seen that the difference between the simulation results and the experimental results is not large, and the simulation results are slightly smaller than

experimental values. This is mainly because the material model used in the simulation process is composed of spherical particle clusters, whereas the material used in the experiment is more irregular. At the same time, the influence of material moisture content was not considered in the simulation process; the actual material moisture content was about 3%, resulting in a smaller self-locking effect and bonding degree among the simulated material particles, and thus causing the discharge time to be less than the experimental value. However, the overall variation trend is consistent, indicating that the model established in this study is feasible.

Table 4 Material parameters of structures and particles in the simulation process[^37]

Tab. 4 Material parameters of structural and particle in the simulation process[^37]

Parameter	Value
Material shear modulus G/MPa	10
Material Poisson’ s ratio ν	0.3
Restitution coefficient between material and funnel e	0.3

Parameter	Value
Friction coefficient between materials μ	0.5
Friction coefficient between material and funnel μ'	0.56
Material density $\rho/(\mathrm{kg}\cdot\mathrm{m}^{-3})$	3 320
Funnel material density $\rho'/(\mathrm{kg}\cdot\mathrm{m}^{-3})$	7 800
Material particle size d/mm	3.3-10
Funnel upper opening diameter D_1/cm	10
Funnel lower opening diameter D_2/cm	5

(a) Device for material accumulation in the test of material accumulation (b) Numerical simulation

Fig. 5 Tests and numerical simulations of material accumulation

Fig. 6 Variation of discharge time with inclination angle of funnel wall[^37]

3 Analysis of factors influencing blockage at the discharge outlet

The blockage phenomenon is affected by many factors, including material properties, equipment parameters, and operating conditions. This section investigates the effects of feed rate, material size, material shape, and material surface friction coefficient on funnel blockage. In the simulation process, materials are injected above the funnel with an initial velocity of 2 m/s. When the material size is very small or the material is very smooth, complete blockage of the material in the simulation is difficult to occur; however, in most cases the material will fill the funnel. To reflect the influence trend of different factors on blockage, the next moment after the material fills the funnel and material overflow occurs is taken as the critical blockage condition to determine the blockage time point.

3.1 Influence of feed rate

The feed rate is a core parameter that determines the flow characteristics of the material. The study found that when the feed rate is less than 120 kg/s, no blockage occurs at the discharge outlet. When the feed rate is greater than 120 kg/s, the variation of the blockage onset time with feed rate is as shown in Fig. 7. It can be seen that increasing the feed rate gradually advances the blockage time point. When the feed rate is lower than 160 kg/s, the blockage time is longer for the polygonal and arc-shaped funnels, mainly because these

Fig. 8

Figure 5: Fig. 8

two types of funnels are outward-convex, with larger volume, which can delay particle accumulation. When the feed rate increases to above 170 kg/s, the blockage time points of all types of funnels are advanced, indicating that the feed rate has a positive effect on blockage. At a feed rate of 200 kg/s, the blockage time points of all types of funnels are approximately the same, indicating that the structural optimization effect of the funnel is limited under high-speed feeding conditions. In addition, the study found that the reverse-arc funnel shows obvious blockage only when the feed rate reaches 180 kg/s, indicating that it has a certain anti-blockage capability.

Fig. 7 Variation of funnel blockage onset time with material feed rate

The variation of material trajectories and velocities before blockage occurs in the straight funnel is shown in Fig. 8. It can be seen that when the feed rate is 120 kg/s, the collision velocity of the material in the middle of the funnel inlet decreases sharply; the velocity of nearly half of the material decreases to about 1.32 m/s. There are a large number of material trajectories at the funnel discharge outlet, indicating that the material has good flowability; when the feed rate is ···

At 160 kg/s, the trajectory lines of the materials at the bottom of the funnel inlet are obviously blue, and the degree of disorder of the material trajectories is greater than that at the feeding speed of 120 kg/s, indicating that collisions between materials and between the materials and the funnel are more frequent at this time. The trajectory lines of the materials at the funnel outlet are significantly reduced, and the material flowability decreases markedly. When the feeding speed is increased to 200 kg/s, the material velocity at the bottom of the funnel inlet is lower than in the above two cases, and there are very few trajectory lines of materials at the outlet. The results show that the greater the feeding speed, the more frequent the collisions between materials and between the materials and the funnel, and the poorer the flowability of the materials.

(a) $v = 120$ kg/s (b) $v = 160$ kg/s (c) $v = 200$ kg/s

Fig. 8 The trajectories and velocity changes of the bulk materials under different feeding speeds before the occurrence of the straight-walled funnel blockage

3.2 Influence of Material Size

The size of the material has an important influence on blockage at the outlet. In the numerical simulation process, the uniformity of the material particle size in a single simulation was first controlled. By adjusting the radius r of the spherical unit, the particle-size changes under multiple working conditions were realized, and the dimensionless parameter $k = r/r_0$ was defined. The

Fig. 9

Figure 6: Fig. 9

Fig. 10

Figure 7: Fig. 10

simulation results show that when $k < 1$, blockage almost does not occur under conventional feeding-speed conditions; for materials with $k = 1$, except for the curved-wall funnel, the other types of funnels exhibit obvious blockage only when the feeding speed reaches 120 kg/s, and the blockage occurs within the first 10 s after feeding begins. Taking the delivery of 1 200 kg of material at a feeding speed of 120 kg/s as a typical working condition, the variation law of the funnel blockage time point with k is obtained, as shown in Fig. 9.

It is found that when $k = 1.0$, blockage occurs only in the curved-wall funnel. When k increases from 1.4 to 1.6, the blockage time point of the curved-wall funnel is greatly advanced; when $k < 1.4$ or $k > 1.6$, the blockage time point of the curved-wall funnel shows no obvious change. For the straight-walled and folded-wall funnels, when k increases to around 1.6, the blockage time point begins to advance significantly, and as k continues to increase, the blockage time point continues to advance. The results show that the larger the material, the more likely blockage is to occur. In addition, the curved-wall funnel does not experience blockage throughout the entire process, mainly because of the guiding effect of the curved funnel wall on large particles.

Fig. 9 Variation of funnel blockage onset time with material particle size

The trajectories and velocity changes of the materials before blockage occurs in the straight-walled funnel are shown in Fig. 10. The results show that when $k = 1.0$, the trajectory lines of the materials at the bottom of the funnel inlet are almost consistent, inclined downward along the funnel wall, and the material flowability is good; when $k = 1.6$, the trajectory lines of the materials at the bottom of the funnel inlet show obvious disorder, and the minimum material velocity is reduced by about one order of magnitude compared with the previous case; when $k = 2.2$, the trajectory lines of the materials at the bottom of the funnel inlet are relatively disordered, and only a small amount of material passes through the funnel outlet. Material size affects the form of material movement at the bottom of the funnel inlet, thereby influencing the degree of material blockage; excessively large material size will significantly reduce its flowability.

(a) $k = 1.0$ (b) $k = 1.6$ (c) $k = 2.2$

Fig. 10 The trajectories and velocity changes of the bulk materials under different material particle size before the occurrence of the straight-walled funnel blockage

Fig. 11

Figure 8: Fig. 11

Fig. 12

Figure 9: Fig. 12

3.3 Influence of Material Shape

The shape of coal particles varies because of differences in their formation processes and geological conditions. Common shapes include block-like, strip-like, and flake-like forms. Numerical models of coal particles with three shapes were established to study the influence of material shape on blockage, as shown in Fig. 11.

(a) Block-like (b) Strip-like (c) Flake-like

Fig. 11 Coal particles with diverse geometries and the numerical models

Let the maximum dimensions of materials with different shapes be the same. The particle sizes were set as follows: block-like, 64 mm $\times$ 64 mm $\times$ 64 mm; strip-like, 16 mm $\times$ 64 mm; flake-like, 16 mm $\times$ 64 mm $\times$ 64 mm. The simulation found that at a feeding speed of 80 kg/s, except for the strip-like material, materials of the other shapes all became blocked within 10 s after feeding began. Even at a feeding speed of 120 kg/s, the strip-like material did not exhibit obvious blockage, whereas materials of the other shapes exhibited blockage essentially within 1 s at a feeding speed of 120 kg/s. This made it inconvenient to analyze the specific blockage process. Therefore, 800 kg of material was conveyed at a feeding speed of 80 kg/s to study the influence of shape on the time point at which blockage occurs.

The blockage process in the straight-line hopper is shown in Fig. 12. At $t = 1.66$ s, all three shapes of material accumulate at the bottom of the hopper inlet; however, the block-like and strip-like materials pass through the junction between the hopper inlet and outlet at medium and high velocities, whereas most of the flake-like material passes through at relatively low velocity. At $t = 3.1$ s, the block-like material becomes blocked at the bottom of the hopper inlet, while the strip-like material still passes through the hopper transition region at medium and high velocities, with no obvious change in the height of material accumulation; although the flake-like material still maintains mobility, the material accumulation increases significantly and most of the material almost stops moving. At $t = 5.4$ s, the flake-like material is completely blocked; although strip-like particles show obvious material accumulation at the bottom of the hopper inlet, they still maintain relatively good mobility.

(a) Block-like

(b) Strip-like

Figure 13: Blockage onset time in funnels with same maximum particle size and varied material geometries

Figure 10: Figure 13: Blockage onset time in funnels with same maximum particle size and varied material geometries

(c) Flake-like

Fig. 12 DEM simulation of particle accumulation and blockage dynamics for materials with diverse geometries

The times at which blockage begins to occur in the hopper for different material shapes are shown in Fig. 13, among which the strip-like material does not become blocked. It can be seen from Fig. 13 that block-like material is more likely to cause hopper blockage than flake-like material. The reason is that when the maximum material size is kept the same, the material volumes differ greatly; in the curved hopper, the time at which blockage occurs for block-like material is delayed compared with flake-like material. The force conditions of the two shapes of material in the curved hopper are shown in Fig. 14. It can be found that the force exerted by the block-like material on the hopper fluctuates more strongly, while the force exerted by the flake-like material on the hopper is more stable. The above results indicate that the curved hopper has a more pronounced obstructing effect on flake-like material, because flake-like particles are not easy to overturn; especially at the convex contour of the curved hopper, they collide more frequently with the hopper wall, causing severe energy loss.

Fig. 13 Blockage onset time in funnels with same maximum particle size and varied material geometries

The trajectories and velocity changes of the materials before blockage occurs in the straight-walled funnel are shown in Fig. 15. The results show that, at the bottom of the funnel inlet, block-shaped materials decelerate to zero because collisions occur among almost all material particles, and then accelerate and flow out of the funnel. For sheet-shaped materials, at the bottom of the funnel inlet, only the velocity of the outer-layer materials attached to the funnel wall decreases sharply, while the inner-layer materials maintain a velocity of about 1.3 m/s and flow out of the funnel. Collisions between rod-shaped materials and the funnel mainly occur in the upper part of the inlet; the velocity of the materials at the bottom of the inlet is markedly higher than in the former two cases. The results indicate that sheet-shaped materials are significantly hindered when adhering to the funnel wall, whereas rod-shaped materials are less hindered by the funnel wall. The reason is that sheet-shaped materials have a lower rotational degree of freedom and are subjected to greater sliding friction during the downward sliding process, whereas rod-shaped particles have a higher rotational degree of freedom and avoid the effect of sliding friction by rolling.

Fig. 14 Analysis of total particle-wall contact forces in curved-walled funnels

Figure 14: Analysis of total particle-wall contact forces in curved-walled funnels

Figure 11: Figure 14: Analysis of total particle-wall contact forces in curved-walled funnels

Figure 16: Blockage onset time in funnels under constant volume with diverse particle shapes

Figure 12: Figure 16: Blockage onset time in funnels under constant volume with diverse particle shapes

(a) Block-shaped

(b) Sheet-shaped

(c) Rod-shaped

Fig. 15 The trajectories and velocity changes of the bulk materials under different geometries before the occurrence of the straight-walled funnel blockage

Keeping the volumes of materials of different shapes the same, the material dimensions were set as follows: block-shaped, 40 mm × 40 mm × 40 mm; sheet-shaped, 16 mm × 64 mm × 64 mm; rod-shaped, 25 mm × 25 mm × 100 mm. During the simulation, no blockage occurred for the block-shaped materials. The blockage onset times in funnels under different material shapes are shown in Fig. 16.

The results show that rod-shaped and sheet-shaped materials begin to block at essentially the same time in the straight-walled funnel. In the broken-line funnel, sheet-shaped materials block earlier than rod-shaped materials; whereas in the curved-walled funnel, rod-shaped materials block earlier than sheet-shaped materials. No blockage occurs in the reverse-curved funnel.

Fig. 16 Blockage onset time in funnels under constant volume with diverse particle shapes

3.4 Influence of the friction coefficient

Changes in the friction coefficient may lead to sudden changes in the flow state and thereby induce material blockage. The friction coefficient of coal-gangue surfaces is affected by many factors and is usually 0.2–0.6. The simulations found that, when the conveying friction coefficient was 0.2, all types of funnels except the reverse-curved funnel exhibited obvious blockage only when the feeding rate was 120 kg/s, and the blockage occurred within 10 s after feeding began. Therefore, at a feeding rate of 120 kg/s, 1 200 kg of material was conveyed, and the material friction coefficient was varied to study its effect on funnel blockage. The study found that no blockage occurred when the friction coefficient was 0.2;

Fig. 17 Variation of funnel blockage onset time with material friction coefficient

Figure 13: Fig. 17 Variation of funnel blockage onset time with material friction coefficient

Fig. 18 The trajectories and velocity changes of the bulk materials under different material friction coefficient before the occurrence of the straight-walled funnel blockage

Figure 14: Fig. 18 The trajectories and velocity changes of the bulk materials under different material friction coefficient before the occurrence of the straight-walled funnel blockage

the funnel blockage time point varied with the friction coefficient···

changes in the coefficient are shown in Fig. 17. The results indicate that, as the material friction coefficient increases, the blockage onset time for all types of funnels advances. The reverse-arc funnel did not experience blockage during the entire simulation process, indicating that the wall structure of the reverse-arc funnel can, by conforming to the material sliding trajectory, play a certain role in preventing blockage.

The changes in material trajectory and velocity before blockage occurs in the straight-walled funnel are shown in Fig. 18. As the material friction coefficient increases, the number of particles passing through the funnel outlet decreases, indicating that the larger the friction coefficient, the poorer the material flowability.

Fig. 17 Variation of funnel blockage onset time with material friction coefficient

(a) $\mu = 0.3$ (b) $\mu = 0.4$ (c) $\mu = 0.5$ (d) $\mu = 0.6$

Fig. 18 The trajectories and velocity changes of the bulk materials under different material friction coefficient before the occurrence of the straight-walled funnel blockage

4 Conclusions

Based on the discrete element method, this study investigated the blockage phenomenon at the funnel outlet during the conveying of coal-mine stone materials. Funnels of different shapes were designed, and the effects of feeding velocity, material size, material shape, and friction coefficient on blockage were discussed. The results show that when the feeding velocity increases from 120 kg/s to 160 kg/s, the blockage onset time advances, and there is no significant difference among funnels of different shapes; as the material size increases, the blockage time of all funnel shapes advances; the arc-shaped funnel has an evident obstructing effect on the flowability of flaky materials; when the friction coefficient increases from 0.3 to 0.6, blockage occurs earlier. The funnel walls of the bent and arc-shaped funnels have a certain ability to delay blockage at the initial stage, but the segmented-slope design and gradual-transition funnel-wall structure cause the materials to collide frequently at the turning points and to produce continuous impacts against the wall surface during sliding, resulting in greater energy dissipation and accelerating the occurrence of blockage. The reverse-arc wall of the reverse-arc funnel can reduce collisions by conforming to the material sliding trajectory and lower resistance, thereby avoiding blockage. Therefore, the reverse-arc design of the funnel has broad application prospects in belt-conveyor material transport operations.

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Note: Figure translations are in progress. See original paper for figures.