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Simulation of Coal-water Mixture Transportation in A Horizontal Pipeline

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Abstract: In order to solve the problem of selecting the model of conveying pump and the inner diameter of conveying pipeline in the process of underground coal-water mixture conveying, and to realize the best conveying effect of coal-water mixture. In this paper, the flow state of coal-water mixture in the pipeline is numerically simulated by CFD-DEM coupling method using EDEM and FLUENT software. The effects of different inlet flow rates and pipe diameters on the conveying effect of coal-water mixtures are investigated, and the conveying results of coal-water mixtures under different conditions are compared to determine the optimal pipe diameter and inlet velocity; under these conveying conditions, the concentration of the mixtures is changed to simulate the conveying process of coal-water mixtures with different concentrations. The results show that with the increase of the inlet flow rate, the mobility of the particles is significantly improved, and the settling speed is slowed down; with the increase of the pipe diameter, the precipitation phenomenon of the particles is more and more obvious, which determines the inlet flow rate of 2.1 m/s and the diameter of the pipe of 65 mm; in the simulation process, the coal-water mixtures with different concentrations show good conveying effects, with the increase of the concentration, the percentage of the coal particles in the upper part of the pipe increases, and the percentage of the particles in the lower part decreases. With the increase of concentration, the percentage of coal particles in the upper part of the pipe increases, and the percentage of particles in the lower part decreases, and no deposition trend occurs. The research in this paper provides a basis for the reasonable setting of the inlet flow rate and the selection of the inner diameter of the conveying pipeline in the actual conveying system, which can help to optimize the conveying parameters and ensure the good transportation effect of coal-water mixtures in the pipeline.

Keywords: Edem; fluent; pipeline transportation.

1. Introduction

Gas problem in coal mining has always been one of the important factors restricting the safe production of mines[1][2]. With the increase of mining depth, the gas pressure increases and the permeability decreases, etc. are becoming more and more serious[3]. It is urgent to take measures to increase the permeability of coal seams, strengthen the effect of gas extraction, and ensure the safe production of mines[4]. Hydraulic punching technology has the effect of widely improving the permeability of coal seams and improving the gas extraction efficiency of coal seams, and is widely used in the process of gas control[5][6]. A large amount of coal-water mixture generated in the process of hydraulic punching is stagnant in the drilling field, which affects the construction efficiency and needs to be processed through the pipeline transportation system to the separation equipment. The pipe diameter design of the conveying pipeline and the selection of the conveying pump are important factors affecting the conveying efficiency, and the determination of a reasonable pipe diameter and conveying speed is decisive for the good conveying effect.

Many scholars have done research on pipeline transportation based on Fluent and Edem simulation software[7]. Wang Zhong-Chang et al[8]. used Fluent simulation to study the change of non-silting flow rate of gangue filling slurry in different angles of the bend, which led to the non-silting flow rate of slurry in different angles of the bend under different inlet velocities. Xu Pengfei et al[9]. used Fluent-Edem to analyze the flow characteristics of the fluid in the vertical elbow to investigate the movement of ore particles at different flow rates. Based on the theory of solid-liquid two-phase flow and particle dynamics, Hao Chuanbo et al[10]. used Fluent to simulate the fluid flow law under the conditions of different coal slurry mass fraction, pipe diameter and inclination angle. Xu Zefeng et al[11]. used theoretical calculations to derive the optimal full pipe rate, based on which the optimal horizontal pipe diameter for conveying different tailings was introduced, and numerical simulation of variable full pipe flow was carried out using Fluent software to prove the feasibility of the optimization scheme by analyzing the pipe pressure and outlet flow velocity. Therefore, in this paper, Fluent-Edem coupling is used to carry out numerical simulation of coal-water mixture conveying state for different conveying pipeline pipe diameters and velocities to ensure the optimal design scheme.

2. Coupling Theory

There are two types of CFD-DEM coupling models that place particles in the fluid for coupling calculations: the lagrangian model and the eulerian model. The difference between the two is that the lagrangian model only considers the momentum exchange between the solid and the fluid, while the eulerian model considers the effect of solid particles on the fluid in addition to the momentum exchange between the solid-liquid two phases. The Lagrangian coupling is relatively less dense compared to the Eulerian coupling and is suitable for solid phase volume fractions below 10%. The advantage of the Eulerian model coupling method is that both particles and fluids can be selected to simulate the most appropriate method for analysis, so as to faithfully and comprehensively reflect the characteristics of the particulate matter, which in turn ensures the reliability of the simulation results. Therefore, after various considerations and comprehensive analysis, this paper decides to choose the more prominent advantages of the double Euler method for simulation and analysis.

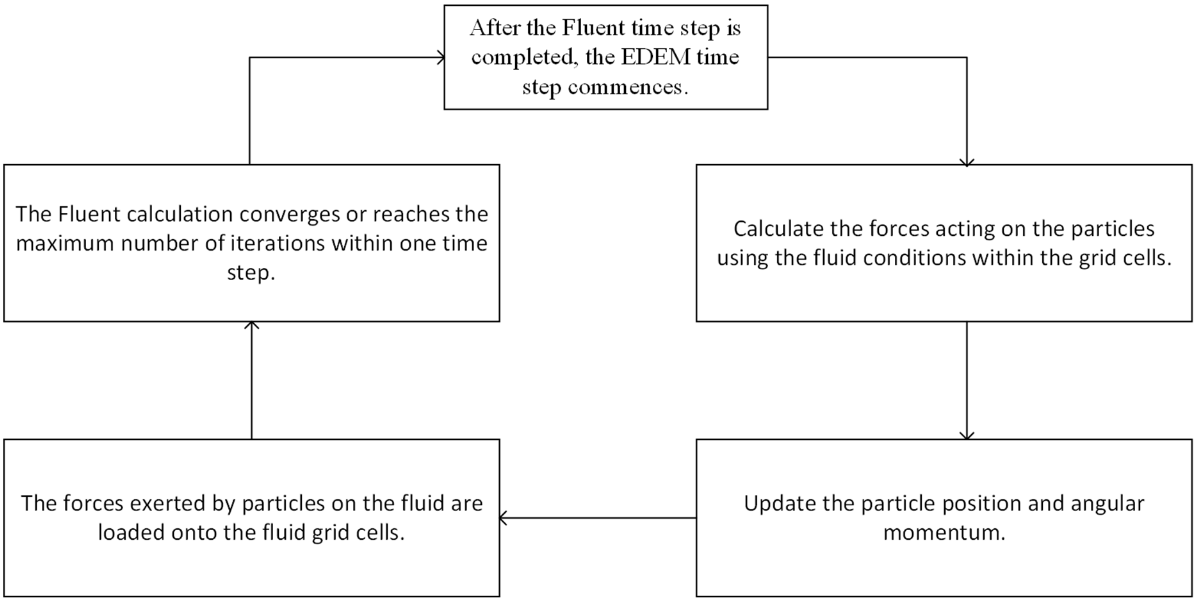


Figure 1. Principle of coupling

As shown in Fig. 1, Fluent-Edem coupling is actually a transient bidirectional data transfer process. When the coupling is performed, the flow field information is first calculated with the help of Fluent software, and in each time step, the Fluent simulation is iterated until convergence. The Edem solver continues the simulation iteratively, calculating the drag force on the Edem particles according to the fluid conditions in the grid cell where the particles are located, and transferring the properties of the particles to the Fluent software through the coupling interface.Fluent takes over the control of the simulation, and then adds momentum to each grid, which is used to represent the effect of the energy transferred to the Edem particles, and calculate the Fluent takes over the control of the simulation, adds momentum to each grid to represent the effect of energy transferred to the Edem particles, calculates the interaction between the particles and the fluid, and transfers the calculated results to the Edem software again based on the coupling interface, and so on until the end of the whole process simulation.

3. Analog Setup

As shown in Fig. 2, a is the Edem pipeline model, which sets the particle factory at the front end of the pipeline at 5 mm and sets a baffle plate at the pipeline inlet to prevent the loss of particles. b is the Fluent computational model, which sets the fluid inlet in Fluent at the same end as that of the Edem particle factory to ensure that the particles can be driven by the fluid to be transported. Both models are cylinders with a length of 1000mm.

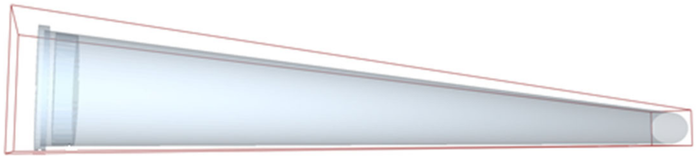


Figure 2. Edem piping model

Figure 3. Fluent piping model

Edem particle plant is set at the top of the cylinder, the particles are modeled as three-sphere particles, and the filling area of the filled particles is the whole cylinder. Rayleigh time step is the ideal dem time step for the time spent by the shear wave propagating in a solid particle, and the set fixed time step should be between 5% and 40% to ensure the stability of the simulation. The Rayleigh time step is calculated to be 3.29e-06 s, and the fixed time step is set to be 1e-06 s, which accounts for about 30% of the Rayleigh time step and meets the stability requirement. The grid size was defined as 6 times the radius of the smallest particle, In addition, Edem saved the data every 0.01 s. The data were saved at 0.01 s intervals.

Fluent simulates the fluid in the pipe with the continuous phase set to water and the discrete phase set to the solid particles generated in Edem. Choose to simulate the transient (Transient) process, pressure base, and gravity set on the y-axis at -9.81m/s2.

The Fluent model is meshed using a 6-sided body with a mesh diameter of 0.002 mm and a mesh number of 1440000. A standard k-ε turbulence model is chosen for the viscous model to describe the fluid flow. The coupling forces between particles and fluid are set up in the discrete phase, including Saffman lift force, virtual mass force, pressure gradient force, bidirectional turbulence coupling, and DEM collision.

The boundary conditions set the inlet as velocity inlet and the outlet as pressure outlet. According to the simulation scheme, different inlet velocities are set. To ensure stable coupling with Edem, the Fluent time step should be an integer multiple of the Edem time step, so the design time step is 0.005s, the number of steps is 100, and the total simulation time is 0.5s.

Table 1. Edem parameter settings

	Poisson's ratio	Density Kg/m3	Shear modulus/GPa
plumbing	0.28	7850	80
granulated (sugar, chemical product)	0.39	2480	0.145

Table 2. Interaction force settings

interact	coefficient of restitution	coefficient of static friction	coefficient of friction
Pellet-Pellet	0.5	0.7	0.1
Pellet-Pipes	0.5	0.6	0.1

4. Simulation

In order to provide a basis for the selection of pipe diameter and conveying pump type, numerical simulation of the conveying speed of coal-water mixture is required. Through the coupled simulation of the flow state of the mixture at different flow rates and the flow state of particles at different pipe diameters, the influence of different flow rates and pipe diameters on the conveying effect of coal-water mixture is analyzed in order to select the appropriate design scheme, and the conveying effect simulation test is carried out according to the determined design scheme.

The simulation scheme is shown in Table 3

Table 3. Simulation scenarios

groups	1	2	3	4	5	6	7
pipe diameter/mm	65	65	65	65	63	65	67
flow rates/m-s-1	1.5	1.8	2.1	2.4	2.1	2.1	2.1

The test program is shown in Table 4

Table 4. Test Program

groups	1	2	3	4
Concentration/%	10	15	20	25

4.1. Numerical simulation of different speeds

The inlet velocity has a significant effect on the settling phenomenon of solid particles, while the settling and transport of particles can be effectively controlled by adjusting the fluid velocity, avoiding the deposition of coal particles at the bottom of the pipeline leading to pipeline clogging, and thus optimizing the performance of the whole conveying system. Therefore, it is necessary to choose a suitable flow rate. The pipe diameter is set to 65 mm, and the initial velocity of the continuous phase is set to 1.5 m/s, 1.8 m; 2.1 m/s, and 2.4 m/s for simulation to select the optimal inlet velocity.

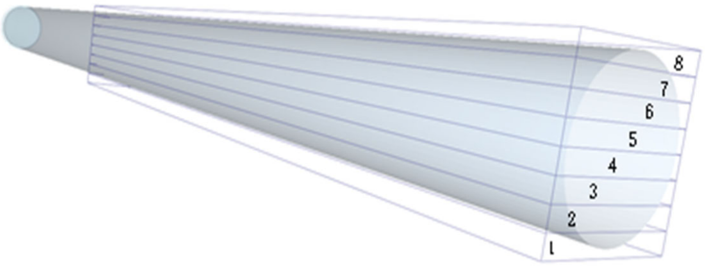
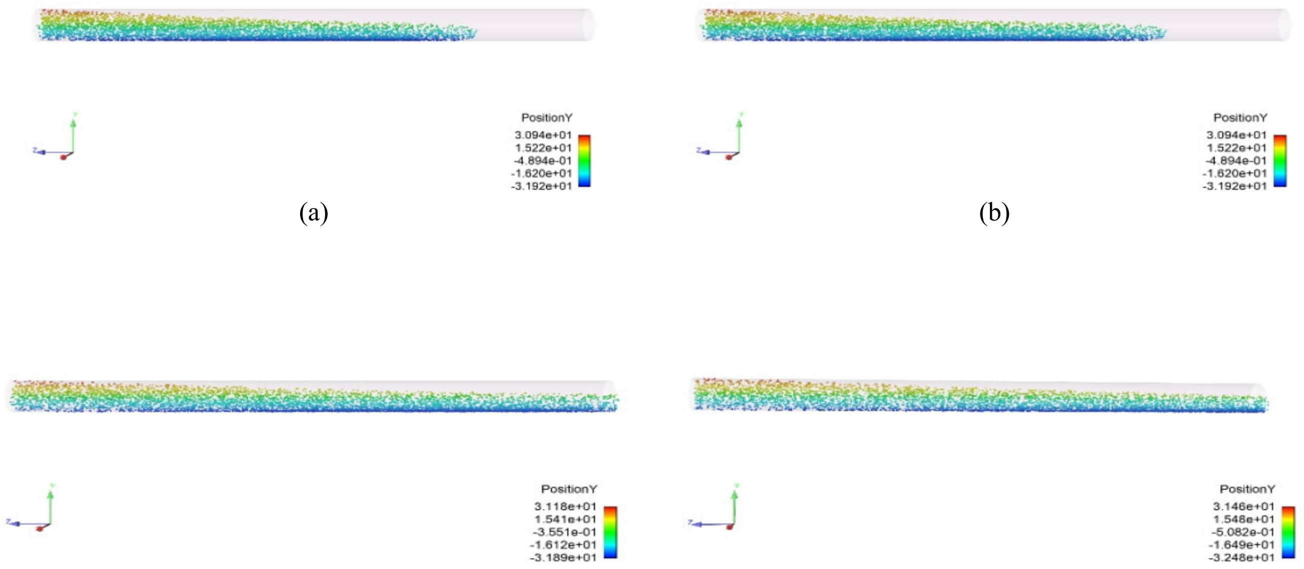


Figure 4. Pipeline Partitioning

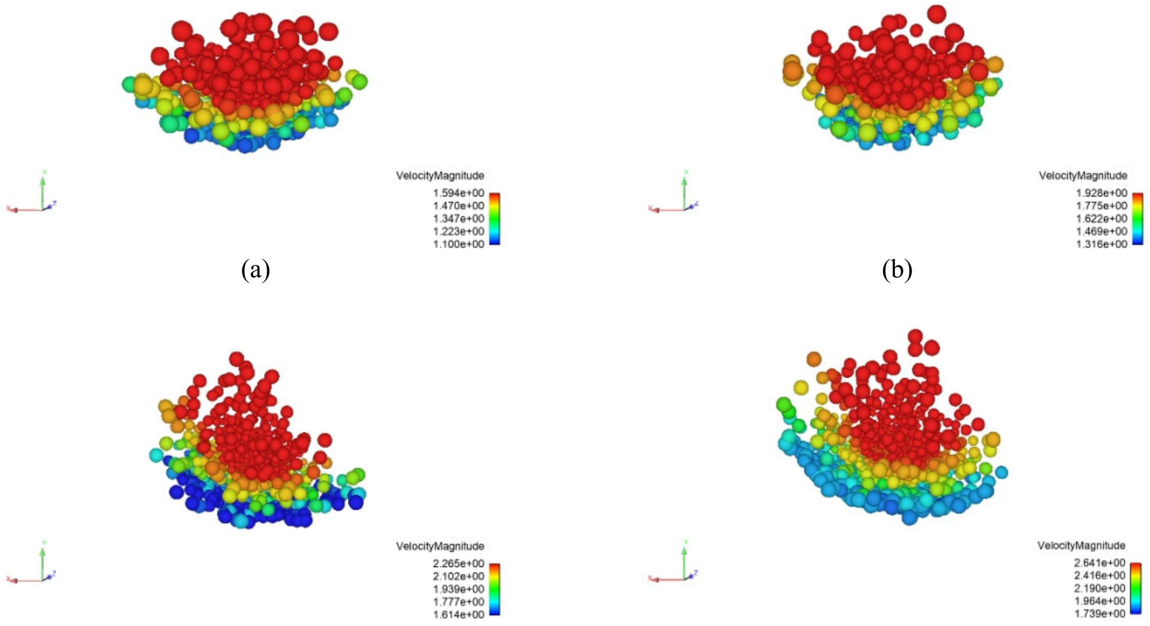
Observe and compare the distribution state of particles in the pipe at 0.5s; at the same time, use Edem post-processing, as shown in Fig.4. Intercept the middle and back section of the pipe, divide it into 8 parts, respectively, carry out the particle statistics and generate the curve graph, analyze the simulation results, each part of the particles accounted for the proportion of the trend with the change of the velocity; take the back section of the pipe, and analyze the velocity of particles at this section.



(a) (b)

(c) (d)

Figure 5. Particle distribution state of 65 mm pipe diameter



(a) (b)

(c) (d)

Figure 6. Particle velocity of 65 mm pipe diameter cross section

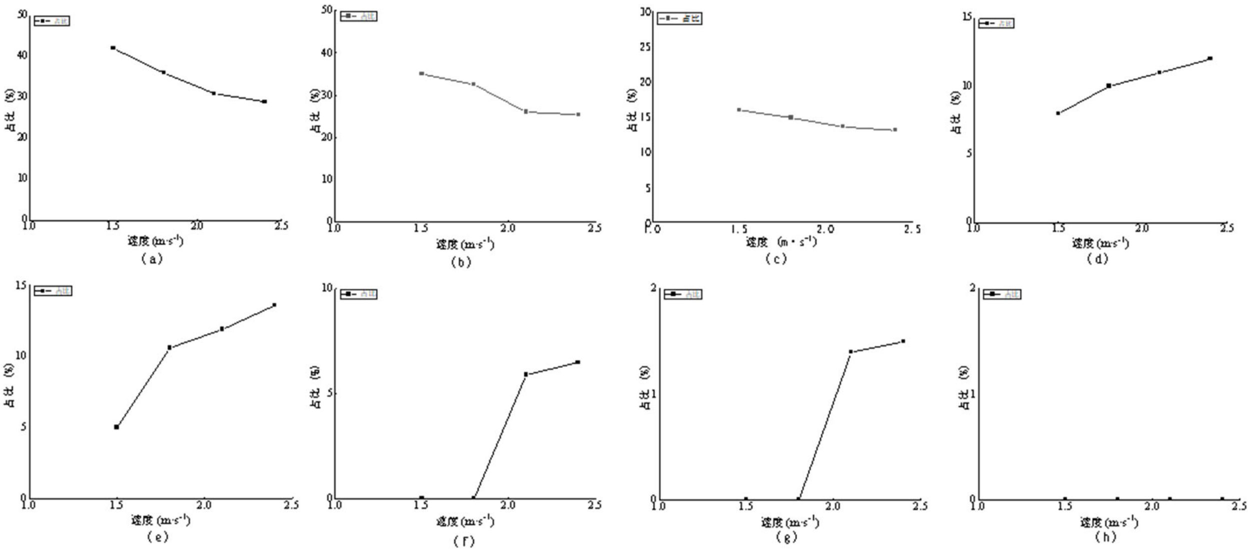


Figure 7. Analysis of regional particle share

As shown in Fig. 5, (a)~(d) are the distribution of particle states with inlet velocities of 1.5 m/s, 1.8 m/s, 2.1 m/s, and 2.4 m/s in turn. From the distribution state diagram, it can be seen that when the inlet velocity is 1.5 m/s and 1.8 m/s, the particles settle at about 100 mm and 150 mm from the inlet, and with the increase of time, the settling phenomenon is more and more obvious, which shows the tendency of intensification with the increase of conveying distance. Compared with the case of 1.6 m/s, the settling phenomenon at 1.8 m/s is relatively weak with transport distance. At an inlet velocity of 2.1 m/s, the particle settling phenomenon occurs at about 200 mm from the inlet, but at about 550 mm, the particle distribution stabilizes with the increase of conveying distance, and the settling phenomenon does not continue to be severe; the change at an inlet velocity of 2.4 m/s is similar to that of 2.1 m/s, but the settling phenomenon occurs later. It indicates that higher inlet velocity is effective in maintaining the suspension state of particles and preventing settling.

As shown in Fig. 6, (a) to (d) are the particle velocity analysis diagrams of pipeline cross-section with inlet velocities of 1.5 m/s, 1.8 m/s, 2.1 m/s, and 2.4 m/s in turn. From the particle velocity analysis, it can be seen that with the increase of fluid velocity, the velocity of the particles are increasing, which means that the particles are more active in the pipeline, and the accumulation of particles in the pipeline can be reduced, which is conducive to the effective transportation of coal-water mixtures.

Each inlet flow rate produces a certain amount of particle settling, and the number of particles in the back half of the pipe varies due to different inlet velocities, so the percentage of particles in each region to the overall particles is counted to analyze the pattern of the percentage of particles in each region at different velocities.

As shown in Fig. 7, (a) to (h) represent the particle occupancy from region 1 to region 8 in turn. As can be seen from the figure, with the increase of inlet velocity, the percentage of particles in region 1, region 2 and region 3 gradually decreases, and there is no big difference in the percentage of particles when the velocity increases from 2.1 m/s to 2.4 m/s; at the same time, the percentage of particles in region 4 and region 5 gradually increases; in region 6, there are no particles when the velocities are 1.4 m/s, 1.8 m/s, and the velocities are raised to 2.1 m/s In region 6, when the velocity is 1.4m/s, 1.8m/s, no particles exist, and when the velocity is increased to 2.1m/s, 2.4m/s, the percentage of particles is increased to 2%; in region 7, with the increase of the velocity, the percentage of particles gradually increases from 0 to 1%; and in region 8, it is all fluid, and there are no particles.

With the increase of speed, the number of particles deposited in the pipeline gradually decreases, and the particles in the upper part of the pipeline gradually increase, indicating that increasing the inlet speed can effectively improve the particle accumulation, and the conveying effect for coal-water mixtures has a greater improvement. When the inlet velocity is increased from 2.1m/s to 2.4m/s, although the conveying efficiency is improved, the enhancement effect is not significant, indicating that in this velocity interval, the effect of the increase in velocity on the distribution of particles tends to be stable.

In view of this, and taking into account the economic benefits and operating costs, 2.1 m/s is selected as the optimal inlet speed, which balances the conveying efficiency and economy, ensures that the conveying requirements are met while avoiding unnecessary energy waste and maximizing cost-effectiveness.

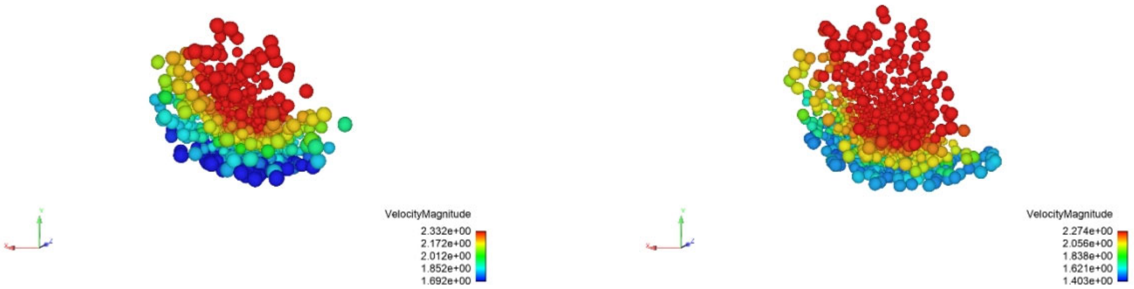
4.2. Page Numerical simulation of different pipe diameters

Pipe diameter size directly affects the operating efficiency and economy of the pipeline. Too small pipe diameter will increase the resistance, increase the power consumption of conveying pumps, reduce the conveying capacity, resulting in a waste of resources; too large a pipe diameter will be a waste of materials, increase the construction cost, increase the operating cost. Choosing the right pipe diameter can improve the operational efficiency and economy of the piping system, reduce energy consumption and maintenance costs.

Therefore, according to the design specification of seamless steel pipe, we design the pipe model with diameters of 63 mm and 70 mm, re-grid the pipe, set the boundary conditions, and set the inlet velocity at 2.1 m/s. When the simulation time is 0.5 s, the distribution state of the particles in the pipeline is analyzed in comparison with that of the pipeline diameter of 65 mm; we also take the rear cross-section of the pipeline, and analyze the radial velocities of the particles in this cross-section and compare with 65 mm. In the same way, the rear section of the pipe is taken to analyze the radial velocity of the particles at this section and compare it with that of 65 mm; using Edem post-processing, as shown in Fig. 4, the middle and rear sections of the pipe are intercepted and divided into eight parts, respectively, to perform the particle counting and to generate the curve diagrams, to analyze the trend of the percentage of the particles in the different parts of the three different pipe diameters in the model.

(a) 63mm (b) 70mm

Figure 8. Particle distribution in 63 mm and 70 mm pipes



(a) 63mm (b) 70mm

Figure 9. Particle velocity analysis of 63mm pipe and 70mm pipe cross section

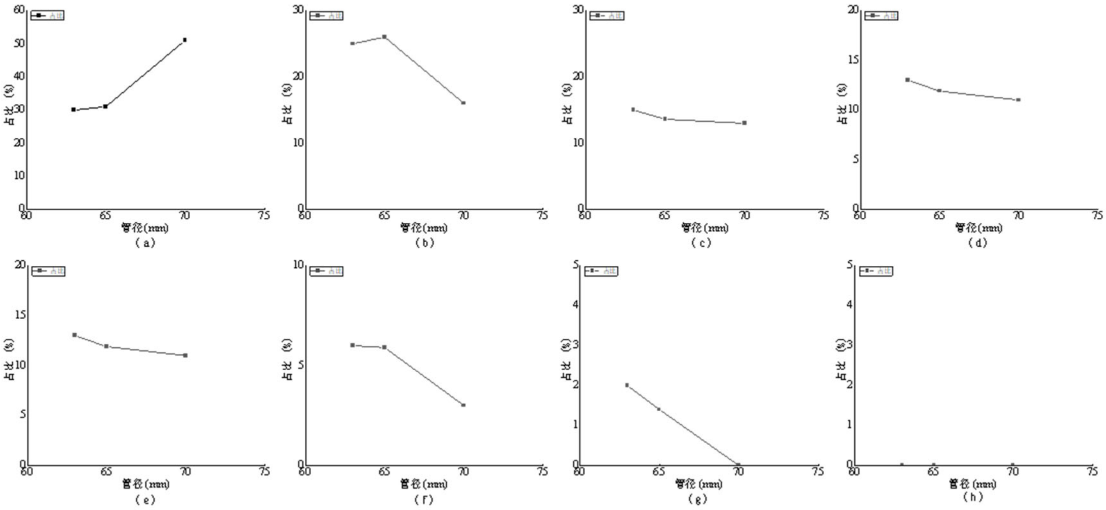


Figure 10. Particle percentage analysis

As shown in Fig. 8, when the pipe diameter was set to 63 mm, it was observed that the particles started to settle at about 300 mm inside the pipe, and the settling phenomenon basically remained stable at 500 mm. At a pipe diameter of 70 mm, the particles settle at about 200 mm inside the pipe, and the settlement becomes more and more obvious with the increase of the transportation distance of the particles. Compared to 65 mm, the settling of particles occurs later in 63 mm pipe diameter and is more pronounced in 70 mm pipe diameter. The accumulation of particles at the bottom is more serious with the increase of pipe diameter.

By analyzing the velocity of particles in the cross-section, it can be seen that the velocity of particles increases when the inner diameter of the pipe decreases from 65 mm to 63 mm. On the contrary, when the inner diameter of the pipe is increased to 70 mm, the velocity of the particles is slowed down. That is, under the same inlet velocity, with the increase of the inner diameter of the pipeline, the velocity of particles in the center of the pipeline increases, which is not conducive to the flow of the coal-water mixture in the pipeline, and it is more likely to occur the phenomenon of coal dust deposition, and the risk of clogging the pipeline increases.

As shown in Fig. 10, (a) to (h) represent the particle occupancy from region 1 to region 8 in turn. The percentage of particles in region 1 increases with the increase of pipe diameter, and the percentage of particles increases by 20 percentage points when the pipe diameter increases from 65 mm to 70 mm. In region 2, 65 mm pipe diameter has the highest percentage compared to other pipe diameters. The change trend of particle percentage in region 3 to region 7 is basic, showing the trend of lower particle percentage with the increase of pipe diameter.

According to the results of the above analysis, when the inlet velocity is the same, the particle flow velocity gradually increases as the pipe diameter decreases. However, the increase in velocity leads to an increase in head loss along the way, which means that for small pipe diameter pipelines, the fluid loses energy faster during transportation and requires greater pressure to maintain the same inlet velocity, and although the cross-sectional particle velocity of 63 mm pipe diameter is higher than that of 65 mm pipe diameter, the transportation effect does not show a very high degree of superiority compared to that of 65 mm pipe diameter. The relatively low pressure loss of large pipe diameters makes it easier to maintain fluid flow under the same dynamic conditions.

This means that a 65 mm pipe diameter is more economical than a 63 mm pipe diameter, which ensures good conveying results, while a 65 mm pipe diameter achieves better conveying results than a 70 mm pipe diameter. In view of this, 65 mm pipe diameter can be selected for coal-water mixture transportation.

4.3. Numerical simulation of different concentrations

In summary, the inner diameter of the transportation pipeline is selected as 65 mm, and the inlet velocity is set at 2.1 m/s. After research, the concentration range of coal-water mixture in the mine is from 10% to 25%. Since the concentration of coal-water mixture directly affects its mobility, there are significant differences in the flow characteristics of coal-water mixtures with different concentrations in the pipeline. In order to verify the transportation efficiency of coal-water mixtures under different concentrations and the adaptability of the pipeline, four concentration points of 10%, 15%, 20% and 25% were selected for simulation verification. To ensure the effective transportation of coal-water mixtures with different concentrations in practical applications.

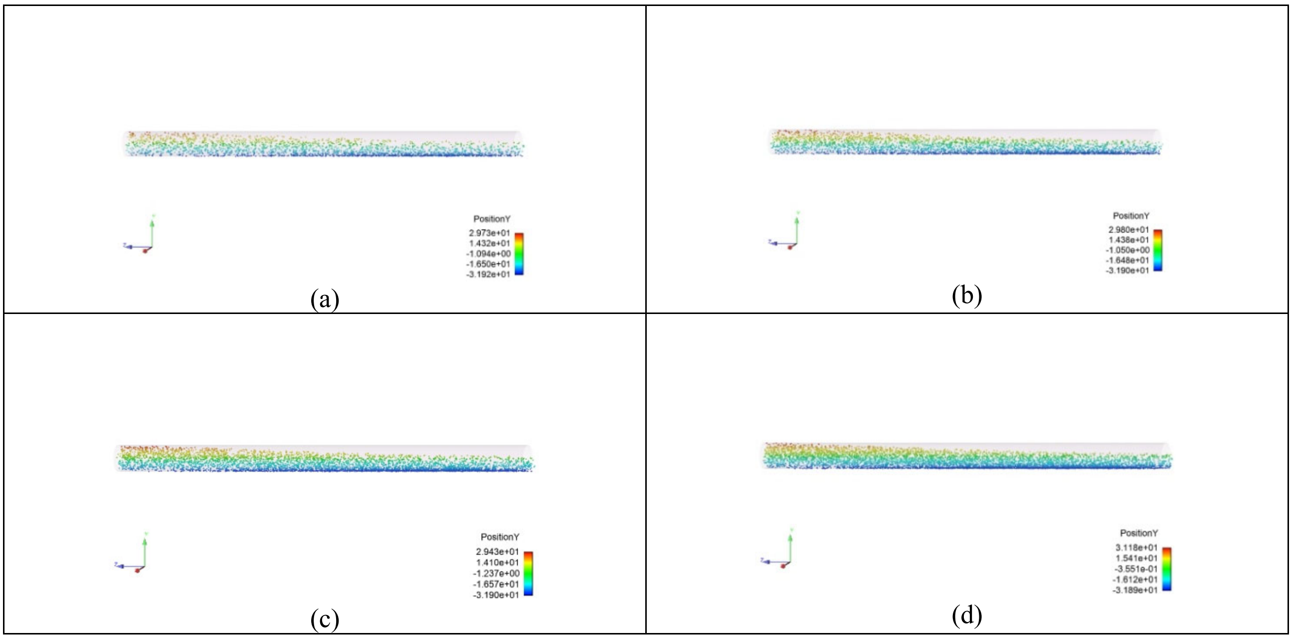


Figure 11. Particle state distribution at different concentrations

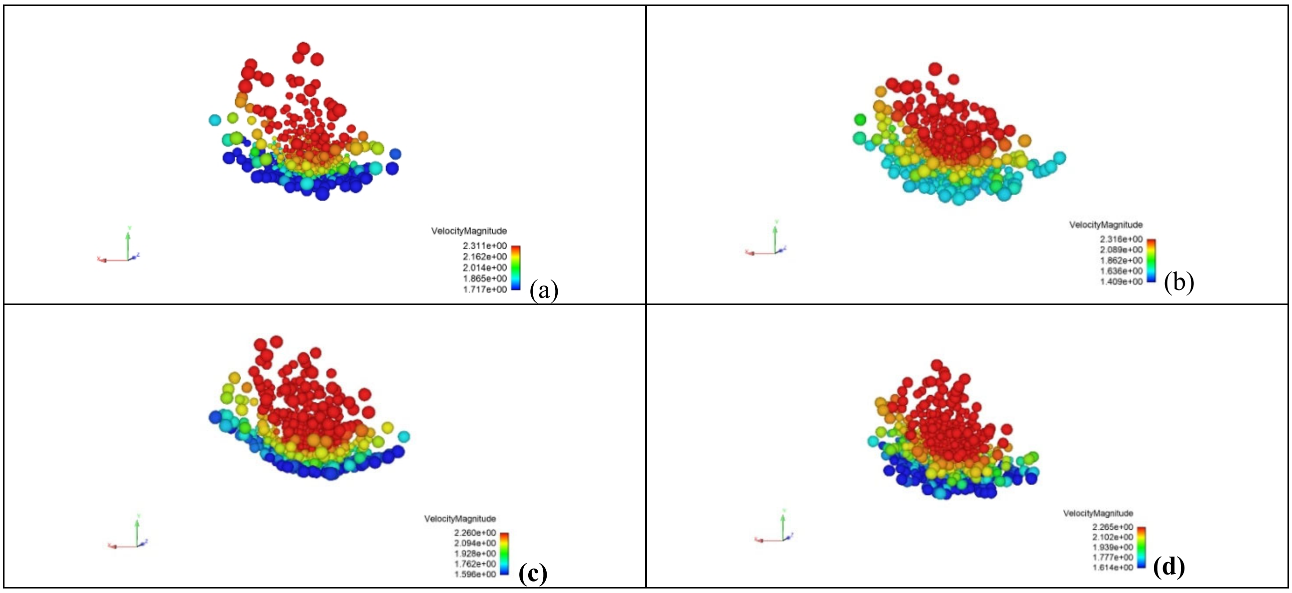


Figure 12. Cross-sectional particle velocity analysis at different concentrations

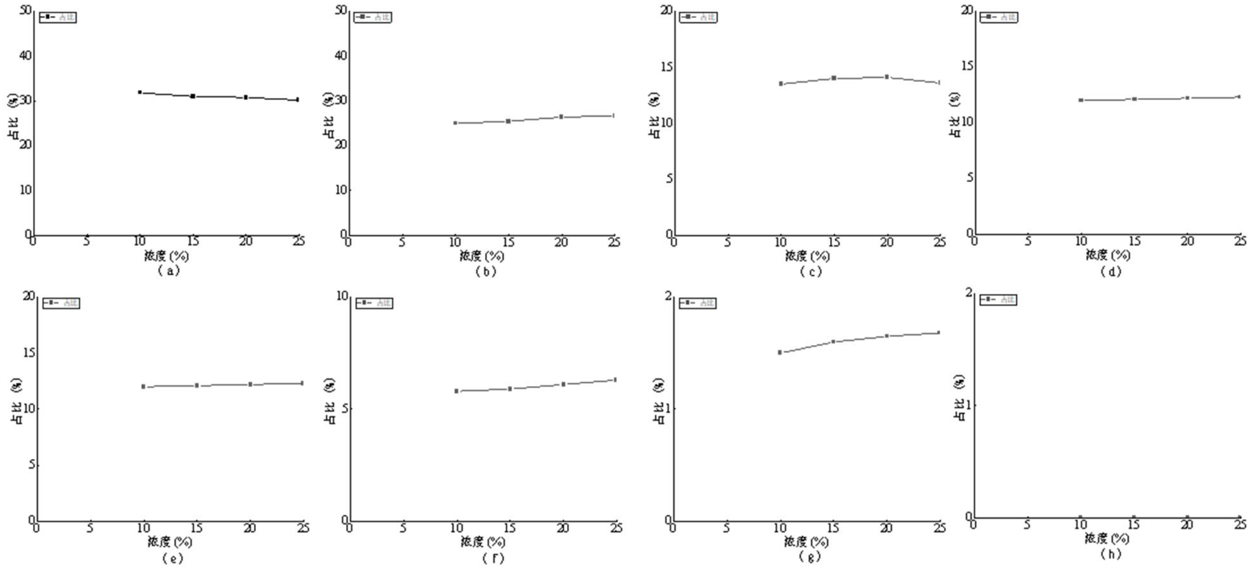


Figure 13. Analysis of the share of each region at different concentrations

As shown in Fig. 11, the degree of particle precipitation in the pipeline decreases with increasing concentration. The transportation state of coal-water mixtures of various concentrations in the pipeline shows a high degree of consistency. The sedimentation phenomenon occurs at about 200 mm from the inlet, and the sedimentation is basically stable at about 500 mm, without continuing serious trend, the flow conditions in the pipeline tend to stabilize, and the solid particles in the coal-water mixture have reached a dynamic equilibrium here, and the overall conveying effect is good.

As shown in Fig. 12, the velocity of coal-water mixtures with four different concentrations is basically the same in the cross-section. The velocity of the particles in the middle of the pipe is 2 m/s, and the velocity of the particles in the lower part of the pipe is slightly smaller than that of the particles in the middle, but the velocity reduction is not obvious, and the flow of the coal-water mixture in the pipe maintains a good uniformity.

As shown in Figure 13, the percentage of particles in region 1 gradually decreases as the concentration increases; the percentage of particles in region 2 gradually increases. In region 3, the percentage of particles decreased after the concentration increased to 20%. The distribution of particles in regions 4 and 5 is basically the same, without large fluctuations, both between 10% and 15%, and the trend shows that with the increase of concentration, the proportion of coal dust particles in the two regions increases. In region 6, the proportion of coal dust particles in coal-water mixtures of various concentrations in this region is between 5% and 10%, and the proportion shows an increasing trend with the increase of the concentration of coal-water mixtures. In region 7, the percentage of coal dust particles in coal-water mixtures of all concentrations was 1% to 2% in this region, and again with the increase in concentration, the percentage showed an increasing trend. No particles were present in region 8.

The results show that with the increase of coal-water mixture concentration, the percentage of coal dust particles in the middle of the pipeline increases and the percentage of coal dust particles in the lower part decreases, and does not show the tendency to be deposited at the bottom of the pipeline due to the increase of coal dust particles. It shows that different concentrations of coal-water mixtures can achieve good transportation effect under this transportation condition.

5. Conclusion

In this paper, the flow state of coal-water mixture in the pipeline is numerically simulated by coupling CFD and DEM methods using Edem and Fluent software, and the optimal conveying inlet velocity and pipe diameter are determined by analyzing the simulation results of different inlet flow rates and pipe diameters. The simulation of the flow state of coal-water mixture with different concentrations in the pipeline proves that the selected inlet flow rate and pipeline diameter can meet the demand of coal-water mixture conveying, and the following main conclusions are drawn:

(1) With the increase of flow velocity at the pipe inlet, the mobility of the particles can be effectively improved, and the settling rate of the particles can be significantly slowed down. The velocity is 1.5 m/s and 1.8 m/s, and the sedimentation increases with the increase of distance. 2.1 m/s and 2.4 m/s tend to stabilize at 550 mm. However, the lifting and conveying effect is not significant from 2.1 m/s to 2.4 m/s. Comprehensive economic benefits, 2.1 m/s is the best speed, balancing the conveying efficiency and cost.

(2) The 65 mm pipe diameter performs optimally in conveying coal-water mixtures. The smaller 63 mm pipe diameter increases the particle velocity, but the energy loss is high and the economic efficiency is low. A larger pipe diameter of 70 mm leads to particle deposition and increases the risk of clogging. Therefore, the 65 mm pipe diameter is the best choice, as it ensures good conveying results and is more economical.

(3) With the increase of the concentration of coal-water mixture, the degree of precipitation of particles in the pipeline is weakened, the transportation condition remains consistent, the velocity distribution is uniform, and the particles show a tendency to be distributed in the middle and upper part of the pipeline. Under the transportation conditions of 65 mm inner diameter of the pipeline and 2.1 m/s inlet velocity, coal-water mixtures of different concentrations can achieve good transportation results. It provides an important reference basis for the pipeline transportation of coal-water mixtures.

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