Study on dust reduction at source technology based on coal particle movement control

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Abstract. Dust control during the transfer process in coal preparation plants presents a significant challenge. To address this problem, a model was developed to analyze dust detachment and adhesion as well as a kinematic model for the coal transfer process. A source-based dust reduction technology was proposed as a solution with specific focus on coal particle flow control. DEM (Discrete Element Method) analysis software was used to conduct a comparative analysis of the coal particle flow dynamics in both conventional and curved coal falling chute systems. A test rig was developed to study dust generation and collection during coal transfer. Experimental and analytical results showed that the curved coal chute design reduced dust generation by 40.96% weight compared to conventional chutes, offering valuable insights for optimizing dust control in coal transfer operations.

1. Current situation and problems of dust prevention and control

Coal processing generated dust, which can – if not controlled - cause environmental pollution, endanger the health of workers, and even pose risks such as dust explosions [1-3]. Dust problems are particularly prominent in transfer links such as chutes, unloading, and coal storage yards [4-5]. China is the largest producer and consumer of coal globally and as such, extensive research in dust prevention and control systems has been pursued. These studies include the construction of fully enclosed coal storage yard blanking, fully enclosed belt conveyor trestle, setting up sealed guide troughs, bag type dust removal, dry mist dust suppression as well as negative pressure induced dust removal systems within the raw coal production system [6]. These measures have progressed the development of dust emission control as well as reducing the associated hazards [7]. However, when the moisture content of coal is low, the amount of dust generated increases significantly which creates operational issues such as dust blockages, uncleanliness, and high dust removal costs [8].

Moreover, in northern China, the temperature in winter often drops to -20 ℃, which brings its own set of problems, especially the systems that use water to control dusting is affected as the spraying of dust removal water droplets can often freeze instantly and lose the function of capturing dust particles [9]. Additionally, introducing water into the system during cold periods exposes the system to chute blockages or could affect the equipment operation due to the frost [10]. By studying the dust generation mechanism in chute transfer, coal unloading and coal storage systems, dust generation from the source can be reduced by

controlling the movement state of coal particles. Ensuring a controlled flow of particles can effectively reduce dust emission and greatly contribute the optimization of the design of dust control system [11-15].

2. Mechanical model of dust detachment and adhesion

The research team of Beijing Huayu Engineering Co., Ltd analyzed the dust generation law in the transfer process of coal preparation plants by studying the mechanism of dust generation [16-18]. A mechanical model for dust detachment and adhesion was designed and constructed [19-21].

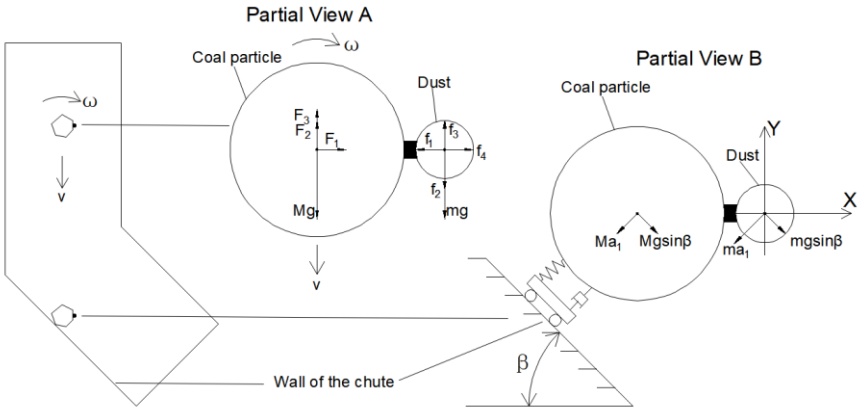


Fig. 1. Force model of dust particles in the chute

During the transfer process of coal at coal preparation plants, which is prone to dust generation, a dust particle may be attached to a larger, adjacent coal particle. Mechanical analysis can be performed at the moment of collision between particle and chute wall as shown in Figure 1.

As shown in Partial View A of Figure 1, a mechanical analysis was performed on falling coal particles and dust. Specifically, M denotes coal particle mass, m denotes dust mass, g is the gravitational acceleration; f_1 and f_2 are the normal and tangential forces exerted by coal particles on dust respectively; f_3 is the air resistance on dust; f_4 is the centrifugal force acting on dust due to the coal particle rotation. F_1 and F_2 are the normal and tangential forces exerted by dust on coal particles respectively; F_3 is the air resistance on coal particles. According to Newton's third law, F_1 is the reaction force of f_1, and F_2 is the reaction force of f_2.

In partial view A of Figure 1[22]:

$$f_3=(1/2)C\rho SV_1^2 \quad (1)$$

In Equation 1: C is the air resistance coefficient; ρ is the air density; S is the windward area of dust; V_1 is the relative velocity between dust and air.

$$f4=mr\omega^2 \quad (2)$$

In Equation 2, r is the radius of the coal particles, and ω is the angular velocity of the coal particles' rotation.

The partial view B of Figure 1 illustrates the coal particle colliding with the chute wall. Due to the short contact time during collision of the particle and the chute wall, friction forces have little effect on the direction of the particles parallel to the chute wall, and the contact surface (chute wall) is assumed to be smooth. As such, the collision model between particles and chute can be approached as a damped nonlinear contact model. Additionally, in Figure 1, β is the inclination angle of the contact surface of the chute; a_1 is the acceleration of particles and dust along the normal direction of the contact surface during collision; Ma_1 is the inertial force along the normal direction of the contact surface when coal particles collide. Mgsinβ is the inertial force parallel to the contact surface when coal particles collide; ma_1 is the inertial force of dust along the contact surface of the chute in the normal direction, and mgsinβ is the inertial force of dust parallel to the contact surface of the chute.

Due to the weight loss of coal particles and dust, the influence of gravity can be ignored when analyzing the interaction force between them.

The force model of dust particles after excluding the influence of gravity is shown in Figure 2. Assuming f_x is the force required for dust and coal particles to detach and adhere in the normal direction, and assuming f_y is the force required for dust and coal particles to detach and adhere in the tangential direction, based on Newton's third law, f_2 is the reaction force of f_3, and f_1 is the reaction force of f_4. f_x is the limit value of f_1, and f_y is the limit value of f_3.

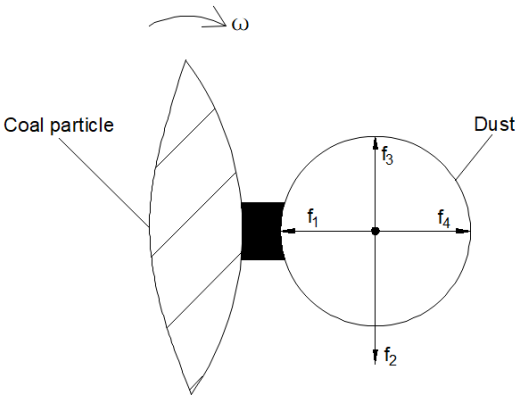


Fig. 2. Dust mechanics model after excluding the influence of gravity

Therefore, the centrifugal force of $f_4 \geq f_x$ for normal detachment of dust, and air resistance $f_3 \geq f_y$ for tangential detachment of dust. Therefore, it is evident that reducing the relative velocity between coal particles and air, as well as decreasing the rotation of coal particles, is beneficial for reducing the probability of dust particles detaching and adhering during the falling process, and for reducing dust generation.

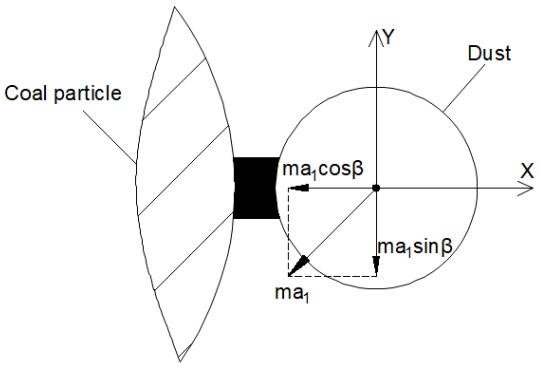
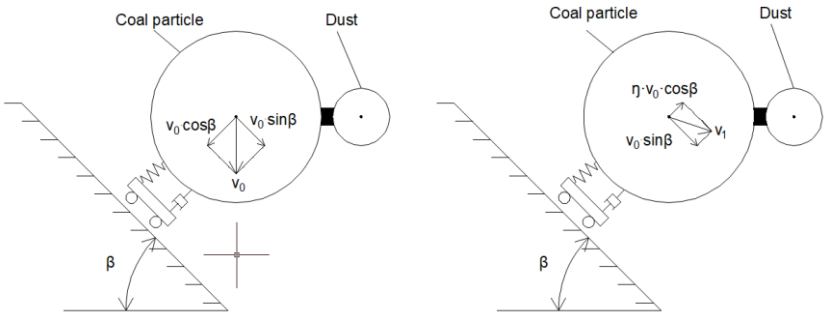


Fig. 3. Particle collision contact mechanics' model

In the partial view B of Figure 1, due to the fact that the inertial force of coal particles and dust along the direction parallel to the contact surface of the chute is a component of gravity, the influence of gravity component can be excluded when analyzing the force during the detachment and adsorption process of dust particles. The mechanical model of dust particle collision after excluding the influence of gravity force is shown in Figure 3. The components of the inertial force ma_1 in the horizontal and vertical directions are $ma_1\cos\beta$ and $ma_1\sin\beta$, respectively. Similarly, $ma_1\cos\beta \geq f_x$ is the condition for normal detachment of dust, while $ma_1\sin\beta \geq f_y$ is the condition for tangential detachment of dust. Therefore, in the case of similar adhesion characteristics, the magnitude of the inertial force ma_1 during collision plays a decisive role in the detachment of dust from adhesion.



（A）Before contact （B）After contact

Fig. 4. Particle collision motion model

As shown in Figure 4, it is the motion model when coal particles collide with the chute. v_0 in the Figure represents the falling velocity of particles at the moment of collision contact; η is the collision velocity rebound coefficient. There is a velocity loss of particles after rebound, that is, the velocity component perpendicular to the chute surface after collision is η times that before collision, where $0 < \eta < 1$.

The impulse of coal particles perpendicular to the contact surface direction before and after collision can be calculated from equation 3 below:

$$I_1 = M \cdot \eta \cdot v_0 \cdot \cos\beta + M \cdot v_0 \cdot \cos\beta = (1+\eta) M \cdot v_0 \cdot \cos\beta \quad (3)$$

Due to the consistent movement of dust and coal particles, the impulse of dust perpendicular to the contact surface before and after collision is:

$$I_2=m\cdot\eta\cdot v_0\cdot\cos\beta+m\cdot v_0\cdot\cos\beta=(1+\eta)m\cdot v_0\cdot\cos\beta \quad (4)$$

Assuming the collision time is t, the average force of the collision is:

$$\bar{F}c=I2/t=(1+\eta)m\cdot v0\cdot\cos\beta/t \quad (5)$$

From this, it can be concluded that when ŋ and m are constant, $\bar{F}_c$ is directly proportional to v_0 and cosβ, and inversely proportional to the collision time t. Therefore, reducing the normal velocity of particles, decreasing the collision contact angle, and prolonging the collision time are beneficial for reducing the impact force generated during the collision process.

3. Dust generation and collection experiment for chute transfer

In order to verify the above analysis, a chute transfer experiment rig was designed to investigate the generation of dust by scaling down the industrial size by 20 times.

3.1 Experimental device design

As shown in Figure 5, the chute transfer and dust collection system include a feeding bin, a feeding belt conveyor, a head funnel, a three-way distributor, a conventional chute, a curved chute, a receiving belt conveyor, a guide chute, a dust collection system, etc.

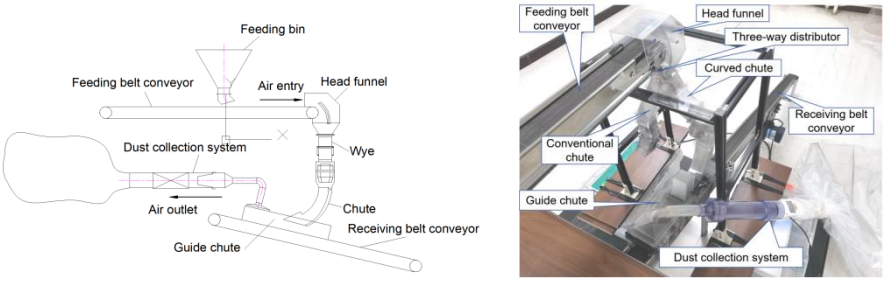


Fig. 5. Structural diagram of the experimental rig

The main technical parameters of the chute transfer system are provided in Table 1.

Table 1. Main technical parameters of the chute transfer system

Belt conveyor width	Sectional dimensions of the chute	Chute height	Length of guide chute	Rated air volume of variable frequency fan
60 mm	40×40 mm	~400 mm	300 mm	54 m³/h

3.2 Discrete element simulation analysis

3.2.1 Material calibration

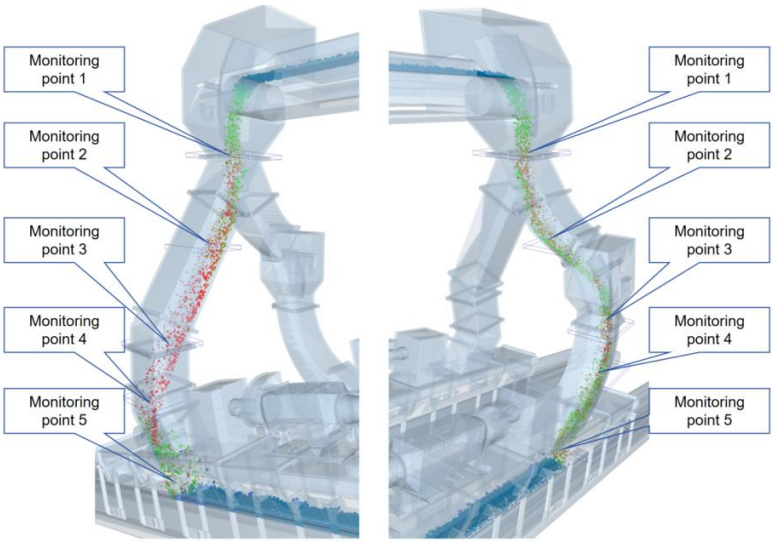
The experiment used raw coal samples from Shaanxi Xiaobaodang Coal Preparation Plant, which were naturally dried and crushed to -3 mm particle sizes. The fraction of -0.5 mm particles is 43.53 %, and the moisture content is 5.87 %.

3.2.2 Analysis and comparison

To analyze the rationality of the structural design and compare the particle flow state, a simulation analysis model was constructed at a ratio of 1:1 to the experimental rig, and a DEM (Discrete Element Method) simulation analysis was performed on the designed experimental rig. The main input data for simulation analysis is shown in Table 2.

Table 2. Main input parameters for discrete element simulation analysis

Material	Feed quantity	Belt conveyor speed
-3 mm Xiaobao Dang raw coal	80 kg/h	0.3 m/s



(a) Conventional chute (b) Curved chute

Fig. 6. Particle velocity analysis diagram of chute

Table 3. Statistical table of particle velocity in the chute

Chute types	Speed (m/s)					
	Point 1	Point 2	Point 3	Point 4	Point 5	Average
Conventional	1.18	1.29	1.73	2.00	1.02	1.44
Curved	1.18	1.01	1.20	1.03	1.06	1.10

Figure 6 shows the analysis diagram of particle velocity inside the chute, and Table 3 provides the statistical data of particle velocity at different positions along the height of the chute.

The material velocity in the conventional chute fluctuates greatly, with an average velocity of 1.44 m/s. The maximum velocity of the material occurs near measurement point 4, with a velocity of 2.0 m/s. The speed of the material contacting the belt conveyor is 1.02 m/s, and the angle of contact with the belt conveyor is about 80 °.

The material velocity inside the curved chute changes smoother and slower, with an average velocity of 1.10 m/s. The maximum velocity of the material occurs near measurement point 3, with a velocity of 1.2 m/s. The speed of the material in contact with the belt conveyor is 1.06 m/s, and the angle of contact with the belt conveyor is about 55 °.

Also, the average rotational kinetic energy of particles in the curve coal chute is 6.90×10^{-8} J, while the average rotational kinetic energy of particles in the conventional chute is 9.40×10^{-8} J, which is 26.60% lower than that in the conventional chute. This indicates that the curved chute reduces the rolling of particles during the transfer process, which reduces the dust generation.

3.3 Dust generation and collection experiment

Dust generation and collection experiments were conducted using the experimental rig for both conventional and curved chutes. The main test parameters for the -3mm Xiaobao Dang raw coal are shown in Table 4.

Table 4. Main parameter settings for chute dust generation and collection test

Chute types	Belt conveyor speed (m/s)	Feeding speed (kg/h)	Feeding time (s)	Induced draft air volume (m^3/h)	Induced draft time (s)
Conventional	0.3	80	90	7	100
Curved	0.3	80	90	7	100

After each experiment, the weight of the collected dust was recorded. The experiment data are shown in Table 5.

Table 5. Statistics of dust collection from chutes

Chute types	Group 1	Group 2	Group 3	Average
Conventional	1.66 g	1.72 g	1.60 g	1.66 g
Curved	0.83 g	1.16 g	0.94 g	0.98 g

It can be seen from Table 5 that under the same conditions, the average dust collection quantity of the curved coal falling chute test is 0.68g less than that of the conventional chute, that is, 40.96% less. Therefore, it can be proved that the structural design of the curved coal falling chute is beneficial to optimizing the movement state of coal particles, thereby significantly reducing the generation of dust.

4. Conclusion

The study constructed a model for dust detachment and adhesion and kinematic model during the transfer process. It was analyzed that, under the premise of certain coal material properties, the relative velocity between particles and air, the angular velocity of particles, the contact angle between particles and the chute during collision, and the velocity along the normal direction of the contact surface during particle collision with the chute are key parameters that affect dust detachment and adhesion. The viewpoint of reducing dust generation from the source by optimizing the motion state of coal particles was proposed. And through DEM simulation analysis, the motion data of coal particles in two structural forms, conventional chute and curved chute, were compared to verify the above viewpoint. An experiment rig for the generation and collection of dust transferred by the chute was further constructed. According to the experimental data, the dust generation of the curved chute is 40.96% less than that of the conventional chute, indicating that the use of a curved chute structure design can significantly reduce dust generation. It is recommended to promote the source dust reduction technology so that can further popularize the clean coal production.

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