International Journal of Mechanical and Electrical Engineering
ISSN: 3005-9615 (Print), ISSN: 3005-7132 (Online)
Volume 8, Number 8, Year 2026
DOI: https://doi.org/10.62051/ijmee.v8n8.01

A Split-type Slag Collection and Dust Removal Device Suitable for Tail Slag Discharge of Shield-unloading Drilling Tools

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ABSTRACT

Aiming at the problem that the shield-unloading drilling tool adopts an internal slag discharge channel, making the traditional borehole-mouth dust removal device difficult to adapt to the shield-unloading drilling tool, this study designed a split-type slag collection and dust removal device adapted to the internal-slag-discharge drilling tool. Through theoretical analysis, numerical simulation and laboratory tests, the structure and operating parameters of the split-type slag collection and dust removal device were optimized and designed. The results show that within the slag discharge wind speed range of 15 m/s, the dust-slag separation box has the separation and settlement ability for coal particles with a particle size larger than 0.3 mm, realizing dry slag removal; the dust removal efficiency of the jet dust removal box first rises rapidly and then tends to level off with the increase of water supply pressure, while the pressure loss increases correspondingly. Under the water supply pressure of about 3 MPa, the average dust removal efficiency reaches 92.2%, realizing wet dust removal.

KEYWORDS

Shield-unloading Drilling Tool; Split-type Dust Removal Device; Dry-wet Separation; Dust Control; Numerical Simulation.

1. INTRODUCTION

In order to solve the problem of slag discharge during drilling in outburst-prone coal seams, Sun Yuning [1] proposed the “shield-unloading” drilling concept: abandoning the external slag discharge channel and constructing an internal slag discharge channel. This design can not only reduce the deflection degree of the borehole, but also improve the stability of the borehole through the shield protection effect of the drill pipe surface. In addition, the slag discharge function of the screen holes on the drill pipe surface can realize the pressure relief of the drill pipe itself, thus effectively preventing the drill pipe from being stuck[2]. Based on the “shield-unloading” drilling concept, the shield-unloading drill pipe is internally provided with three channels: an axial air supply channel, a radial screen hole channel and a central slag discharge channel. The axial air supply channels are arranged at intervals along the circumference of the drill pipe; a plurality of radial screen holes are arranged on the drill pipe body at positions avoiding the axial air supply channels, and the center of the drill pipe is the internal slag discharge channel. The radial screen holes connect the inside and outside of the drill pipe, while the axial air supply channels and the radial screen holes are not connected with each other. The pressure air flow enters the drill pipe through the air supply channel; a large amount of drilling slag produced by the bit breaking coal and the borehole wall collapsing enters the internal slag discharge channel in the center of the drill pipe through the screen holes, and is discharged outward under the action of the air flow [3-4].

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Dust produced by underground operations not only threatens the health of miners, but also affects production safety[5-6]. The data show that new pneumoconiosis cases in coal mines account for more than 70% of all new occupational disease cases; nationwide, this proportion is also as high as more than 55% [7]. In addition, coal dust and gas both have explosion risks. When the two are mixed, the lower explosion limit will be reduced and the explosion power will be enhanced. The shock wave generated by coal dust explosion propagates extremely fast. When propagating in the roadway, it will make the settled coal dust re-raise, and may even cause coal breakage and generate new coal dust, finally triggering secondary or even continuous explosions [8]. The explosion impact may also damage the support equipment, and in severe cases even cause the roadway to collapse. Therefore, coal dust poses a serious threat to the life safety of mine workers. Reducing the dust concentration in the working environment and ensuring the life safety of workers has become an urgent task.

This study focuses on the dust removal technology and equipment related to gas drainage borehole operations, and designs a dust removal device adapted to the internal-slag-discharge drilling tool. Through dust control, the device can improve the air quality in coal mines, reduce safety hazards, ensure the health of workers, and contribute to the application of shield-unloading drilling tools in coal mine operations.

2. DESIGN SCHEME AND NUMERICAL SIMULATION OF THE SPLIT-TYPE SLAG COLLECTION AND DUST REMOVAL DEVICE

The shield-unloading drilling tool adopts the internal slag discharge channel design, and the drilling slag is discharged from the tail of the drill pipe rather than from the borehole mouth. In order to solve the dust removal problem caused by its slag discharge characteristics, a split-type dust removal device was designed, which adopts a two-stage treatment mode combining dry slag removal and wet dust removal.

As shown in Figure 1, during the drilling process of the shield-unloading drilling tool, the drilling slag and air flow are discharged through the internal slag discharge channel at the tail of the drill pipe, and are directionally transported to the air supply and slag discharge hose through the sliding sealed pipe. The length of the sliding sealed pipe is designed to cover the maximum exposed section of the drill pipe outside the borehole, and is equipped with an auxiliary pipe-moving device to realize synchronous extension with the connection of drill pipes, ensuring sealed transportation in the whole process and avoiding the escape of air flow and drilling slag.

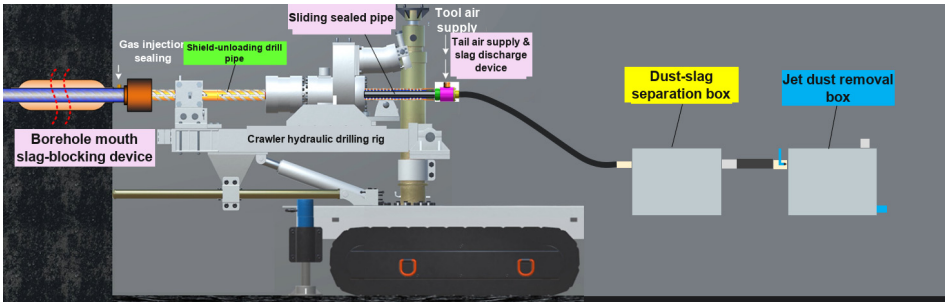


Figure 1. Schematic Diagram of the Split-type Dust Removal Device for Shield-unloading Drilling Tools

2.1. Numerical Simulation of the Dust-slag Separation Box

2.1.1. Computational Model Settings

The Fluent software was used to carry out the numerical simulation analysis of the flow field of the dust-slag separation box. Through the numerical simulation analysis, the flow field distribution

characteristics inside the box can be deeply studied, providing reliable data basis for the subsequent structural optimization and improvement.

When solving the converged solutions of the velocity field and pressure field, the SIMPLE algorithm was selected. As a semi-implicit pressure correction method, the SIMPLE algorithm continuously adjusts the pressure field through iteration until the convergence conditions are satisfied. The relevant calculation conditions and model settings are shown in Table 1.

Table 1. Computational Conditions and Model Settings

Computational conditions and model	Setting
Operating pressure	101325 Pa
Gravitational acceleration	−9.8 m/s²
Solver	Pressure-based; steady state; absolute velocity
Turbulence equation	k-ε
Energy equation	Off

Considering the complexity of particle movement inside the dust-slag separation box, the Discrete Phase Model (DPM) was used to simulate the movement characteristics of coal dust particles. Based on the Lagrange coordinate system, this model tracks the discrete phase and simultaneously considers the momentum, energy and mass exchange between the discrete phase and the continuous phase [9].

The main function of the dust-slag separation box is to settle and separate coal slag particles. The diameter of coal particles was set to 0.3 mm, which is within the distribution range of underground drilling slag and conforms to the synergistic action range of gravity and inertia separation theory [10]. At the same time, fixing the particle size helps to simplify the model and balance the accuracy. The main settings of the discrete phase model and particles are shown in Table 2.

Table 2. Discrete Phase Model and Incident Particle Parameter Settings

Setting	Parameter
Maximum number of steps	50000
Step length factor	5
Injection source type	Surface
Particle type	Inert
Diameter distribution	Uniform
Particle density (kg/m³)	1400
Particle diameter (mm)	0.3
Total flow rate (kg/s)	0.2

2.1.2. Boundary Condition Settings

In this study, the inlet boundary condition was set as a velocity inlet to simulate the initial velocity of the fluid entering the dust-slag separation box. Considering that the wind speed at the drill tail will attenuate with the increase of drilling depth, the inlet wind speed was set to 15 m/s. At this time, the actual slag discharge wind speed will be greater than 15 m/s, which can ensure the stable discharge of the drilling slag. The outlet was set as a negative pressure outlet. According to the test measurement of the dust removal box, with the change of water supply pressure, the average negative pressure at the inlet of the dust removal box pipeline is about 600 Pa, so the outlet gauge pressure of the separation box was set to −600 Pa. The boundary condition settings are shown in Table 3.

Table 3. Boundary Condition Settings

Boundary condition	Setting
Inlet boundary type	Velocity inlet
Inlet velocity	15 m/s
Turbulence intensity	5%
Outlet boundary type	Pressure outlet
Outlet gauge pressure	−600 Pa

2.1.3. Simulation Analysis of Inlet Velocity and Slag Baffle Position

The movement of the fluid inside the dust-slag separation box was simulated when the inlet velocity was 15 m/s and the distances from the slag baffle to the air inlet were 100 mm, 150 mm, 200 mm and 250 mm, respectively, and the velocity field distribution contours and particle movement trajectories were obtained. Through the analysis of the relationship between the velocity flow field distribution characteristics and the particle movement trajectories, the appropriate installation position of the slag baffle was determined.

2.1.4. Flow Field Analysis

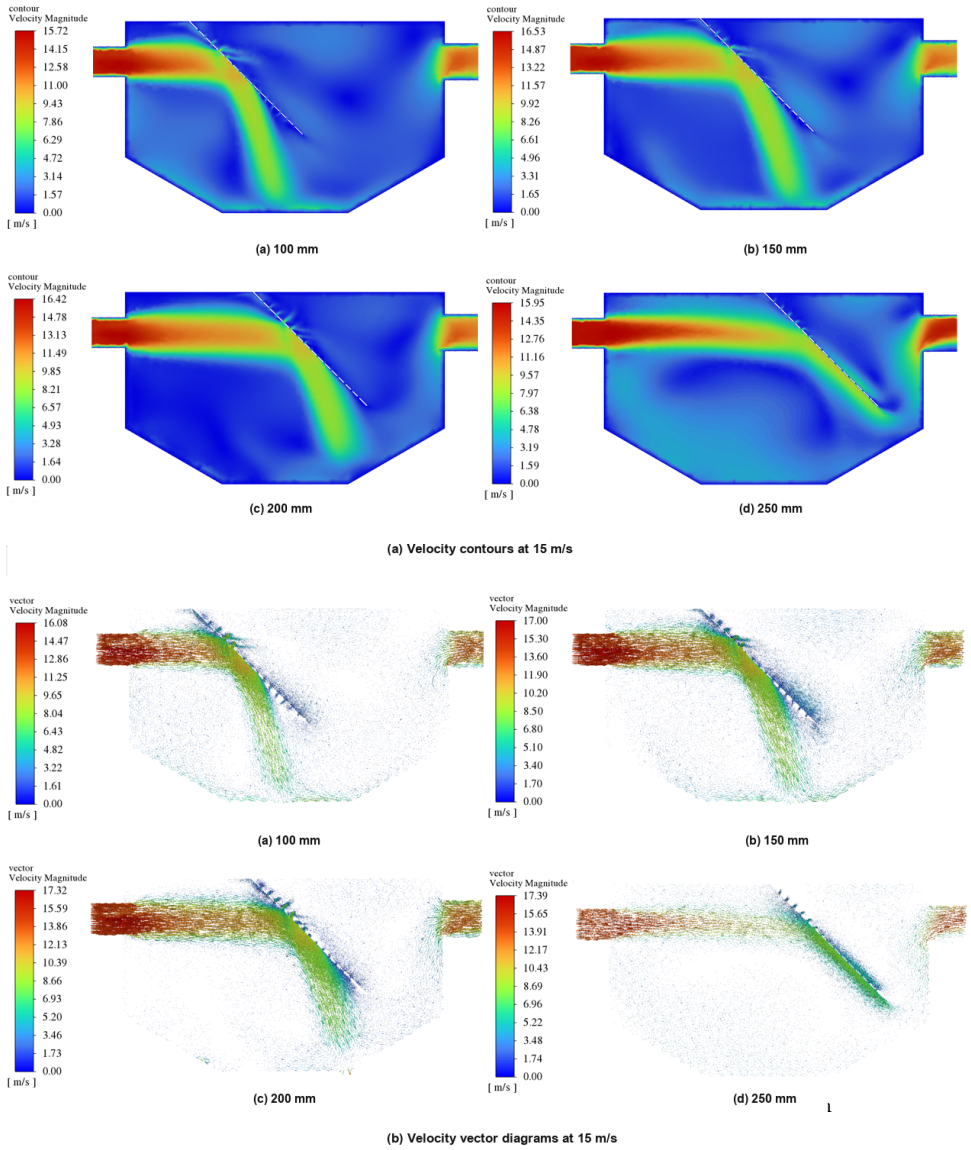


Figure 2. Velocity Contours and Vector Diagrams at Different Slag Baffle Positions at a Wind Speed of 15 m/s

As shown in Figure 2, the slag baffle distance has a certain influence on the uniformity of the flow field. When the slag baffle distance is relatively small, the high-speed air flow directly impacts the leading edge of the slag baffle, forming a significant velocity gradient concentration zone, and a local velocity concentration zone is generated on the windward side of the slag baffle. The vector diagram shows that obvious flow separation occurs in this area, forming a clockwise rotating vortex. Such a

vortex will hinder the diffusion flow of the air flow to the bottom of the box, resulting in poor flow field uniformity.

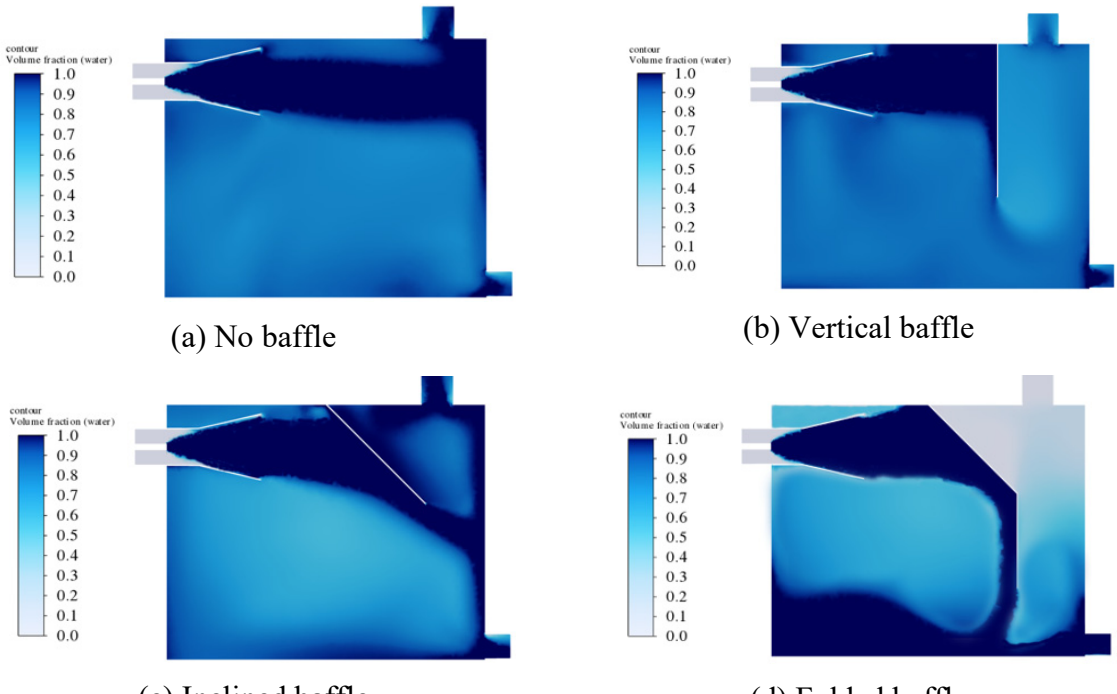
The comprehensive results show that the slag baffle distance of 150 mm can better balance the uniformity and stability of the flow field under different inlet velocities, providing a favorable flow field environment for particle settlement and separation. Under low-speed conditions, this distance can maintain high flow field uniformity and good particle settlement effect; under high-speed conditions, this distance can effectively reduce the large-scale vortex behind the slag baffle, reduce the local velocity pulsation, reduce the sudden change of velocity gradient at the end of the box and the secondary reflux near the wall, thereby improving the particle settlement efficiency.

2.2. Numerical Simulation Analysis of the Jet Dust Removal Box

In the setting of boundary conditions, both the pipeline air inlet and the nozzle water outlet were set as pressure inlet conditions; the baffle wall was set as a no-slip wall; and the exhaust outlet and drainage outlet were set as pressure outlets. In the calculation process, the second-order upwind discrete scheme was selected, and the simulation results were obtained through the transient iteration method. The relevant boundary condition settings of the numerical simulation are shown in Table 4.

Table 4. Simulation Condition Settings of the Jet Dust Removal Box

Setting	Type
Solver	Pressure-based
Body force	Implicit
Gas-liquid surface tension	0.072 N/m
Inlet boundary	Pressure inlet
Outlet boundary	Pressure outlet
Inlet pressure	3 MPa



(a) No baffle (b) Vertical baffle

(c) Inclined baffle (d) Folded baffle

Figure 3. Liquid Phase Distribution Contours of the Jet Dust Removal Box with Different Baffle Configurations

In the study of the flow field characteristics of the jet dust removal box, the influence of different baffle configurations on the movement characteristics of the atomized droplets in the box was compared and analyzed, as shown in Figure 3. Finally, the folded baffle design scheme was adopted. In this scheme, the inclined baffle acts as the main guiding structure, which can change the flow path of the high-speed water flow and make it diffuse gently along the inclined surface; the vertical baffle is arranged below the inclined baffle, which enhances the overall stability of the flow field by blocking the reflux and constraining the fluid disturbance.

3. LABORATORY EXPERIMENT AND RESULT ANALYSIS

A test system of the split-type dust removal device was built to simulate the dust removal process under actual working conditions, as shown in Figure 4.

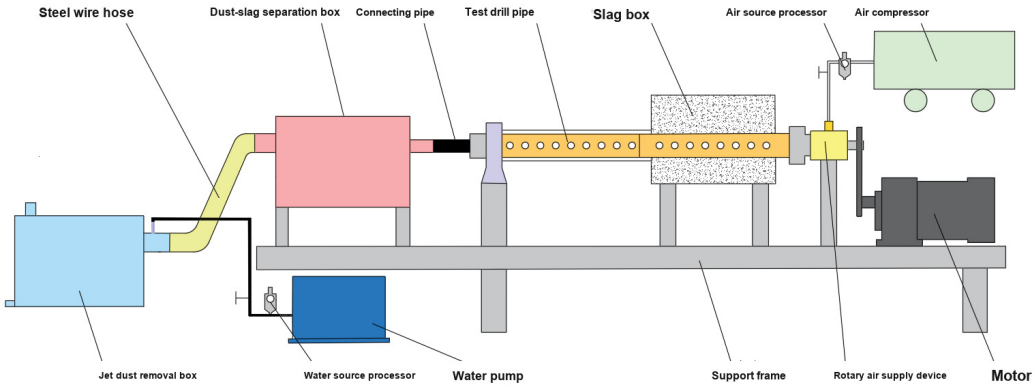


Figure 4. Schematic Diagram of the Laboratory Test of the Split-type Dust Removal Device

3.1. Experimental Result Analysis of the Dust-slag Separation Box

Under the slag discharge wind speeds of 10 m/s, 15 m/s and 20 m/s, the coal slag particles settled by the dust-slag separation box were collected, and the masses of coal slag particles with different particle sizes were screened and weighed. The obtained test data are shown in Table 5. The distribution characteristics of the mass proportion of different particle sizes in the total settled mass were sorted out and summarized, as shown in Figure 5, and the settlement performance and dust-slag separation function of the device were analyzed. The following conclusions were drawn:

Table 5. Mass Distribution of Coal Particle Sizes

Diameter (mm)	<0.1	0.1-0.3	0.3-0.5	0.5-1	1-2	2-3	>3
Initial mass (kg)	1.57	3.25	3.94	4.65	2.98	2.02	1.59
Mass at 10 m/s wind speed (kg)	0.02	0.04	0.43	1.01	1.31	0.89	0.68
Mass at 15 m/s wind speed (kg)	0.01	0.03	0.32	0.56	0.83	0.75	0.59
Mass at 20 m/s wind speed (kg)	0	0.02	0.11	0.34	0.54	0.50	0.48

The dust-slag separation box can settle and separate coal slag particles with a particle size larger than 0.3 mm within the wind speed range of 10–20 m/s, which verifies that the device has the dust-slag separation function. Among them, the fine coal dust particles enter the jet dust removal box under the effects of dynamic entrainment and negative pressure ejection; the dust-slag separation creates graded treatment conditions for the wet dust removal of the subsequent dust removal box, which conforms to the design requirements of the split-type dust removal device.

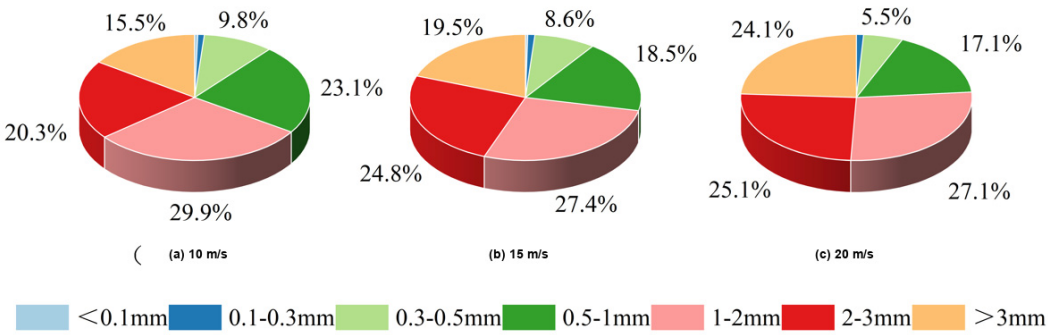


Figure 5. Mass Distribution Proportion of Settled Coal Particles at Different Wind Speeds

3.2. Experimental Result Analysis of the Jet Dust Removal Box

By regulating the dust concentration at the inlet of the dust removal box to 100, 150 and 200 mg/m³ respectively, and setting five gradients of water supply pressure from 1 to 5 MPa, the dust removal efficiency and pressure loss of the dust removal box under different water supply pressures and dust concentrations were measured and calculated. Through the data analysis of the dust removal efficiency under different water supply pressures, the influence law of the pressure parameter on the water mist dust removal efficiency was systematically revealed. The test data are shown in Figure 6.

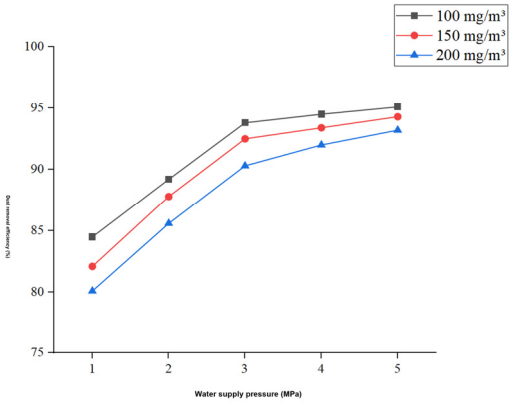


Figure 6. Variation of Dust Removal Efficiency of the Jet Dust Removal Box under Different Working Conditions

Combined with the change law of the dust concentration, when the inlet dust concentration increases, the solid phase particle density per unit volume increases, and the effective contact ratio between droplets and dust decreases. Comprehensively considering the dust removal efficiency and energy consumption control, the water supply pressure of about 3 MPa was selected as the water supply pressure of the jet dust removal box. Under this working pressure, a balance between the dust removal efficiency and energy consumption control was achieved, and the average dust removal efficiency was 92.2%.

4. CONCLUSION

Aiming at the characteristics of tail slag discharge of the internal slag discharge channel of the shield-unloading drilling tool, combined with the actual factors, a split-type dust removal device suitable for the shield-unloading drilling tool was designed, and the structure and operating parameters of the device were optimized and analyzed through the combination of theoretical analysis, numerical simulation and laboratory tests.

The performance of the split-type dust removal device was verified through laboratory tests. The dust-slag separation box has significant separation and settlement ability for coal dust particles with

a particle size larger than 0.3 mm within the slag discharge wind speed range of 10–20 m/s, effectively reducing the load of the subsequent dust removal box and realizing dry slag removal. Under the water supply pressure of about 3 MPa, the average dust removal efficiency of the jet dust removal box is 92.2%, and the average pressure loss is about 0.7 kPa, realizing wet dust removal.

Through the dry-wet synergistic effect, the split-type dust removal device realizes dry slag removal and efficient coal dust control, meets the coal dust control needs of the shield-unloading drilling tool, has practicability and feasibility, and provides a reference for the design of dust removal devices under similar working conditions.

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