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Research article

Optimization study on the application of induced dust suppression cover in primary crushing station of open-pit mine

Tong Wua [a], Zhuo Yanga [a,*], Kai Zhanga [a], Bo Wangb [b]

[a] China Coal Technology & Engineering Group Shenyang Engineering Company, LiaoNing, China
[b] China Coal Technology & Engineering Group Chongqing Research Institute, ChongQing, China

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ABSTRACT

Aiming at the problems of large dust production, high dust removal cost and poor dust suppression effect of primary crushing station in open-pit mine, the new type dry device-dust suppression cover was put forward, which induced dust to complete the circular clean movement with closed loop eddy current inside the enclosure by means of pressure balance and closed loop flow. After field application, it was found that the dust suppression effect of the device was not ideal and it was seriously affected by wind. By means of fluid dynamics simulation, the structure of the device was optimized for design and engineering application. The simulation results showed that the optimized device enhanced the overall upward movement trend of the internal air flow, weakened the transverse movement trend of air flow, and blocked the interference of ambient wind, which can effectively inhibit the driving effect of overdraft on dust dispersion. The monitoring results showed that the dust concentration around the optimized device was significantly lower than that before optimization, and the lowest concentration can reach 0.33 mg/m^3, which met the requirements of environmental protection emission.

1. Introduction

Open-pit mining is a complex and orderly evolution process of large-scale earthwork crushing, migration, abandonment and remodeling, in which a large amount of dust will be produced by the destruction and disturbance of each production operation. Dust pollution in open-pit mine not only has a negative impact on the surrounding environment, harms the health of workers, causes premature wear and tear of equipment parts, but also reduces the working efficiency of the mine production system [1] (see Figs. 1 and 3).

The dust generated by the unloading operation of the primary crushing station in open-pit mine is one of the important sources of dust pollution in open-pit mine. Dust control of crushing station is also a key and difficult point in green mining. On the one hand, the unloading port of the crushing station is an open working environment, and the surrounding airflow movement law is complicated, which is sensitive to the change of influencing factors. On the other hand, the collision, extrusion and crushing of materials in the process of unloading will lead to dust flying and aggravate the dust pollution at the discharging port [2].

At present, in terms of dust pollution and control in open-pit crushing station, experts and scholars at home and abroad have actively carried out analysis and exploration by simulation analysis software combined with experiments and field tests.

Jing Deji et al. used numerical simulation to analyze the variation characteristics of vortex blowing-suction dust removal flow field,

* Corresponding author.
E-mail address: yangzhuo@zmsyy.com (Z. Yanga).

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built simulation test model to study the optimal vortex performance parameters of equipment, and compared and analyzed the dust removal performance between vortex blowing-suction and single suction [3]; Chen Xi et al. introduced the numerical simulation method in the research process, whose results showed that in the crushing station, various factors will affect the generation of dust, such as air shock wave wind, induced wind speed, blanking and crushing, traction wind flow, etc. It is difficult to remove the positive pressure of the unloading point and actively control the concentration of dust by sprinkling water [4]; Ma Yundong et al. used numerical simulation to explore the force law of dust particles, construct a specific motion model whose motion trajectory can be mastered by Lagrange method [5]. It is concluded that the dust concentration in the diffusion space is positively correlated with the emission intensity of dust sources, and is seriously affected by wind conditions.; Pope A M et al. used the vorticity calculation method to explore the free turbulent flow field formed by gas and solid phases, and solved the induced gas flow rate with the help of particle dispersion behavior and Lagrangian discretization flow field [6]; Allcott and Hunt conducted in-depth research and analysis through numerical simulation to explore relevant influencing factors, mainly involving particle distribution and height [7]; Moin and Parviz focused on the study of dust movement with wind flow, so as to clarify the influence of wind speed on dust movement. The simulated wind speed value was higher than the actual one, but there is no significant difference between the two [8]; Gas-solid two-phase flow theory is now widely used in industrial and mining enterprises, which is involved in coal mining, metallurgy, energy and other industries. The transportation, unloading and crushing of coal in the operation process of crushing station are also involved in the study of gas-solid two-phase flow theory. Qualitative and quantitative analysis of gas-solid two-phase flow model is conducive to the improvement and optimization of model parameters, so as to achieve the purpose of effectively controlling the dust movement trajectory [9,10].

Wang Suyun et al. explored the movement law of pulverized coal under the effect of airflow disturbance through gas-solid two-phase flow model, and gave its influencing factors [11]. It is concluded that the initial velocity and direction of dust released by different dust sources are obviously different with various wind speeds in the jet attachment area. And the dust is mostly the result of upward movement of dust from above sources under the influence of the initial air flow; Bao Jun et al. conducted a numerical simulation study on the dust collecting mechanism of non-dynamic dust removal system based on gas-solid two-phase flow [12]. It is concluded that dust escape is caused by the comprehensive action of various air currents. The material accelerates in free fall in the state of dispersion, and generates negative pressure to disturb the surrounding air and form high speed induced air currents.

At present, dust removal methods of crushing stations are mostly single closed or wet water spraying measures, which exhibit high equipment operation cost, large water consumption, heavy maintenance workload and strong seasonality, and unsatisfactory dust suppression effect [13]. The existing closed dust suppression facilities are mainly the covers of simple maintenance structures [14]. And there are few related studies, mainly field experiments and practical engineering applications [15,16].

In this study, a new type of dust suppression device for crushing station was proposed and optimized. With the help of numerical simulation, the diffusion distribution and movement trajectory of the dusty air in the dust suppression device - micro-dynamic induction dust suppression cover of the crushing station were explored. Combined with technical demonstration analysis and field monitoring, the device can achieve the best dust suppression effect in practical engineering. The process and conclusion of this study provide new ideas and methods for the application of fluid dynamics simulation and the research of dust control measures.

2. Development and application of device

2.1. Optimization design of device

The dust diffusion range generated by crushing station is affected by various factors such as external wind, bin structure form, vehicle load, unloading height and so on. Reasonable consideration of the above factors is crucial to the dust control effect of the unloading port of crushing station. The main point of dust control in the process of truck unloading in the crushing station is to conduct targeted research on the generation mechanism of dust source at the unloading port and the movement trend of dusty air flow. Dust pollution can be effectively suppressed only by correct intervention of dusty airflow direction.

Research shows that amounts of induced wind will be introduced into the coal bin in the process of unloading by dump truck, and

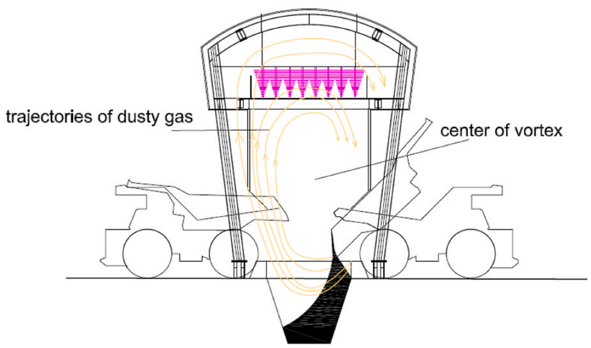


Fig. 1. Schematic diagram of induced circulation dust suppression.

high-pressure gas will be generated in the closed space of the body. Under the action of high-pressure gas, serious dust spraying will occur in the leaky seam of the body, the transfer point at the discharge port of the crusher and the coal leakage transfer point of the scraper [17]. At the same time, collision and extrusion between materials in the process of falling will further aggravate microminiaturization and dust pollution at the discharge port [18].

Based on the above analysis, the project team researched and designed a kind of micro-power induced dust suppression cover for the primary crushing station of open-pit mine. The dust removal idea of dust suppression cover is based on the aerodynamics. Under the action of pressure difference, the change of pressure field in the process of truck unloading can induce the dusty gas to move in the confined space according to the established trajectory, so that the dusty gas can pass through the dust suppression area regularly. When the material falls to the entrance of the drop-off point of the receiving pit, there will be a certain accumulation space. According to the principle of energy conservation, part of the potential energy will be converted into reverse kinetic energy. The larger the mass of particles and dust, the greater the reverse speed. Movement trend of the dusty gas can be controlled by inducing fan. The dust suppression layer in the dust suppression area can not only filter the dust, but also significantly slow down the eddy current field, and realize self-dust removal in a certain confined space by the eddy current field. Finally, under the pressure difference between the negative pressure area of unloading and the positive pressure area of induced space, the dusty gas enters the negative pressure area of unloading again and completes a cycle.

Through theoretical deduction of the mechanism of induction and dust suppression in the truck unloading process of the primary crushing station of open-pit mine, combined with simulation research and process structure demonstration, the project team carried out a complete industrial scheme design of the micro-power induced dust suppression cover, and finally carried out the demonstration engineering application of the device.

2.2. Engineering applications

The team selected Dananhu open-pit mine in Hami, Xinjiang as a pilot to carry out the demonstration engineering application research of dust suppression cover. Hami open-pit mine is located in the Gobi dune plain and low hilly area in the southern part of the eastern Turpan-Hami Basin. The terrain is high in the north and south and low in the middle. And the average annual wind speed is about 3 m/s. The mining technology of this mine area is a discontinuous mining technology combining open-pit shearer and truck. Semi-mobile crushing station is adopted in the mining area. The crushing station is a small receiving bin, of which the head size is 6 m $\times$ 4 m, the lower pit wall is 45° inclined. And there is a 0.8 m high baffle at the pit head. The crushing station is discharged on both sides, with a total capacity of 63.2 m^3. And the load of mine dump truck is 40 tons.

According to the actual operation parameters and external conditions of the crushing station in Dananhu open-pit mine, team members designed the targeted device scheme, and then carried out the production and actual project construction after demonstration. The project covers an area of about 60 m^2. The cornice is 11 m high and the ridge is 12.5 m high. The dust suppression cover demonstration project has gone through several main stages, such as foundation engineering construction, steel structure main construction, membrane structure construction, fan and filter layer process installation, etc. At present, installation and debugging of the device has been completed, and the demonstration project is in the trial operation stage.

During the test operation, it was found that the dust suppression effect of the dust suppression cover device was seriously affected by the external wind conditions, especially when the opposite wind passed through the unloading process, dust would escape from the unloading screen on the opposite side of the unloading. In order to further explore the dust dispersion process, the researchers conducted simulation modeling and analysis on the actual operation of the engineering application device.

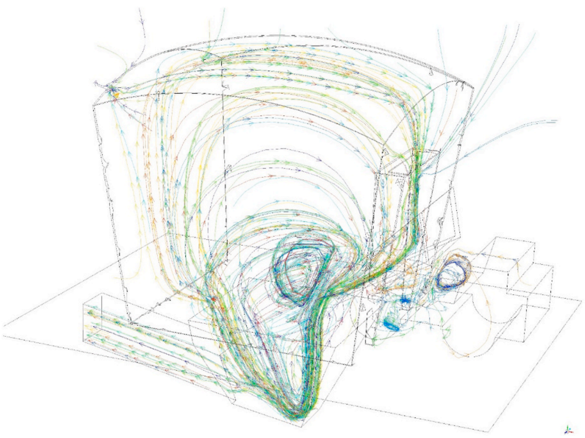


Fig. 2. Flow track during unloading operation.

2.3. Simulation modeling of field application

In order to deeply explore the movement law of dusty air under the influence of wind conditions from a microscopic perspective, this study conducts simulation modeling and simulation analysis on the dust suppression cover and the surrounding dust suppression space.

The model tool is Fluent 13.0 numerical simulation software, which can solve the multiphase flow problems including particles, droplets and bubbles while calculating the fluid flow transportation equation. In this simulation, the mathematical model of airflow and dust particle coupling was adopted, with the air flow as the background fluid and the dust phase as the second phase fluid. The governing equations of the flow are the three dimensional incompressible Navier-Stokes equations, and the turbulent flow is the k-ε two-equation model, in which only momentum transfer is considered and heat transfer is ignored. The mathematical equation is mainly used to determine the velocity field and pressure distribution of gas in working face [19].

The geometric model centered on the dust suppression cover was established and the mesh was divided. The model included unloading port of crushing station, dust suppression cover, dump truck and surrounding drainage basin. In order to ensure the calculation effect, the dimension of the outflow field is set as 30 m in length, 25 m in width and 25 m in height considering the area affected by the ambient wind. The load of dump truck was set to 40 tons. The unloading process lasts 30 s.

The mesh file was imported into Fluent solver, and the solver, model, boundary conditions and dust source parameters were set. Referring to the actual environmental wind speed, the simulation condition is set as the perennial wind speed of 3 m/s in the mining area. The detailed solver, model and boundary condition setting are shown in Table 1 below, and the parameter setting of dust source is shown in Table 2 below.

2.4. Simulation exploration

In order to explore the actual migration and change process of dusty air flow in the dust suppression cover and grasp the movement and distribution of dust in dusty air flow, analyzing the distribution of gas flow field in the process of unloading is the first prerequisite (see Fig. 4). The perennial characteristic wind speed of 3 m/s in the mining is introduced to simulate the movement process of dusty airflow under the external ventilation condition. And the flow field distribution of dusty airflow in the simulation domain is shown in Fig. 5(a–d) below.

By analyzing Fig. 5, it can be seen that the dusty gas presents an inward turning eddy motion trend in the flow field inside the cover body: Dusty gas will form a certain accumulation space when it falls to the dumping point with the material. According to the principle of energy conservation, part of the potential energy is converted into reverse kinetic energy, and dusty gas will spread around with a large amount of air again, forming a closed-loop eddy motion trend. However, due to the impact of ambient wind, the draft wind formed inside the cover body to weaken the above movement trend, and amounts of dusty gas was ensnared to form a low-speed turbulence zone along the horizontal direction and escape from the opposite side of the discharge port. The simulation results of the dust flow trajectory is basically consistent with the field situation.

3. Research on simulation application of optimization

3.1. Optimization design of device

In order to eliminate the negative impact of ambient wind on the dust suppression effect of the dust suppression cover, researchers

Fig. 3. Dust escapes when the wind blows.

Table 1
Parameter setting of solution, model and boundary.

Parameter	Setting
Solver	Uncoupling
Time	Transient
Turbulence model	Standard k-epsilon
Discrete phase model	YES
Energy	No
Turbulence intensity	5%
Hydraulic diameter	10 m
Type of entry boundary type	Velocity-inlet
Type of exit boundary	Out-flow
Surface condition	Trap-no slip

Table 2
Parameter setting of dust source.

Parameter	Setting
Solver	Uncoupling
Size distribution	R–R
Type of jet source	Surface
Discrete phase model	YES
Energy	No
Mass flow rate	1000 kg/s
X	Direction : 0
Initial velocity	Y Direction : 0
Z	Direction : -3 m/s
Turbulent diffusion model	Random orbit model

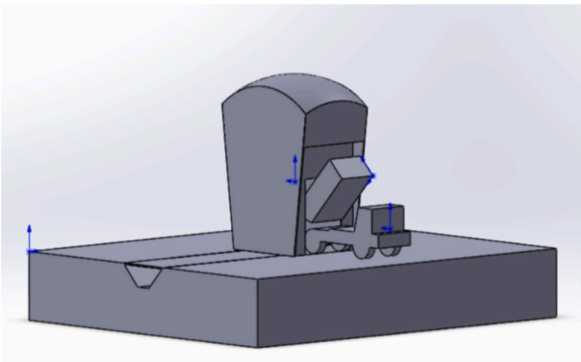


Fig. 4. The modeling result of dust suppression cover.

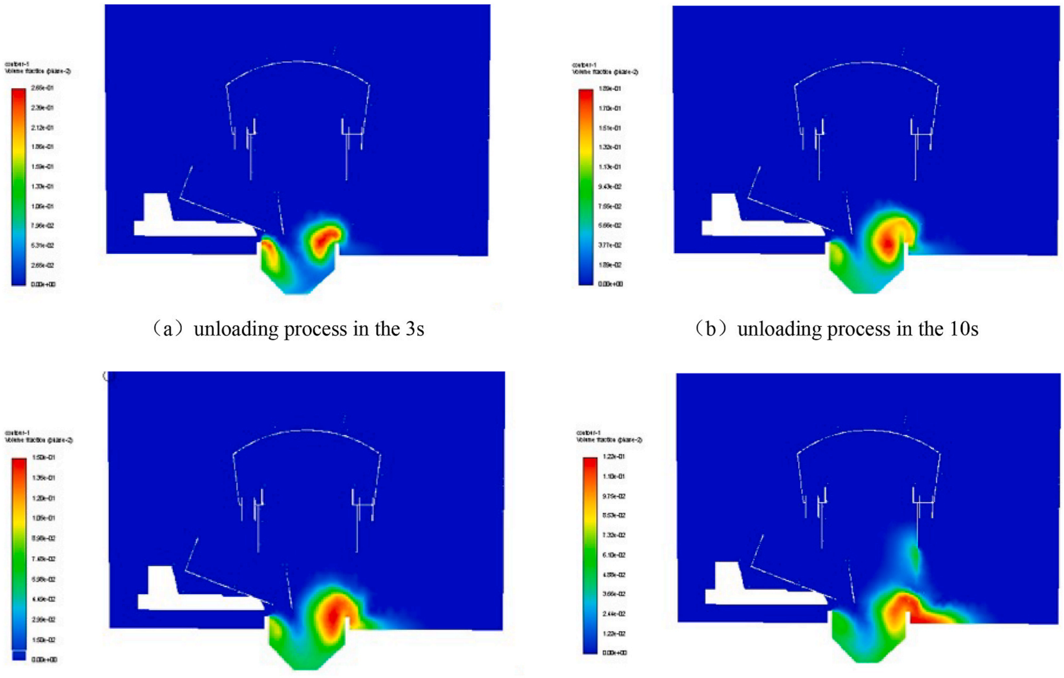
optimized the structure of the device. Firstly, the inner sail is installed inside the cover body to block the formation path of draft wind and weaken the influence of ambient wind. Secondly, negative pressure and explosion-proof fans are installed above the discharging port to ensure that the relative negative pressure is maintained inside the cover body, which enhance the circulating cleaning potential energy of dusty gas inside the cover body and inhibit the dust from escaping outward. The researchers carried out simulation analysis and technical demonstration on the dust suppression effect of the improved device.

3.2. Analysis of simulation

The simulation model of the dust suppression cover was re-modeled. The center of the cover body is provided with occlusion. And three fans were set above each discharge port. The external computing range remains unchanged. The result of re-modeling is shown in Fig. 6.

In order to verify the auxiliary function of fans and the inner sail on the dust suppression effect of the device, the changes in the flow field inside the hood caused by the fan operation were first simulated, and the distribution of the flow field inside the hood under static wind conditions was obtained, as shown in Fig. 7(a-d)below.

According to the analysis of Fig. 8, under the traction of the wind power of the fan, the air flow inside the cover formed a trend of upward movement against the wall of the inner sail on the opposite side of the discharge. At the same time, it was isolated by the inner sail and finally settled at the opposite discharge port under the gravity condition.



（a）unloading process in the 3s （b）unloading process in the 10s

（c）unloading process in the 20s （d）unloading process in the 30s

Fig. 5. The distribution of dusty airflow.

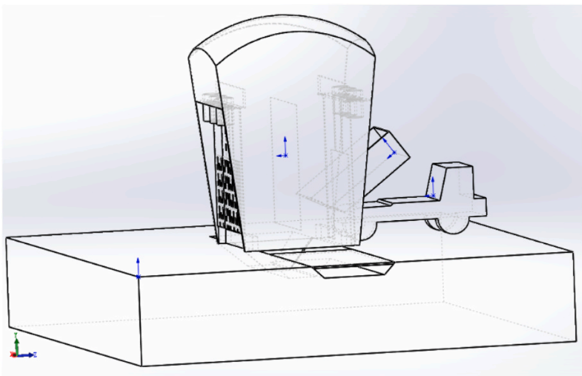


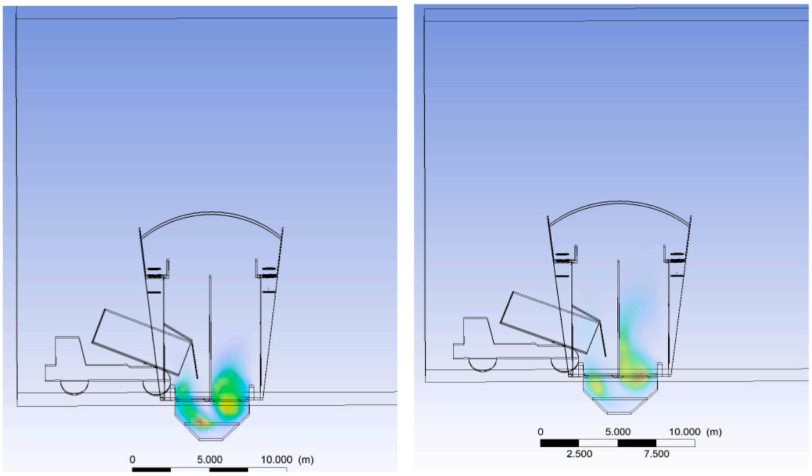
Fig. 6. The result of re-modeling.

The use of fans and the inner sail enhances the overall upward trend of the internal airflow, and weakens the airflow lateral movement trend of dissipation, which can effectively restrain the promotion of dust escape by overdraft.

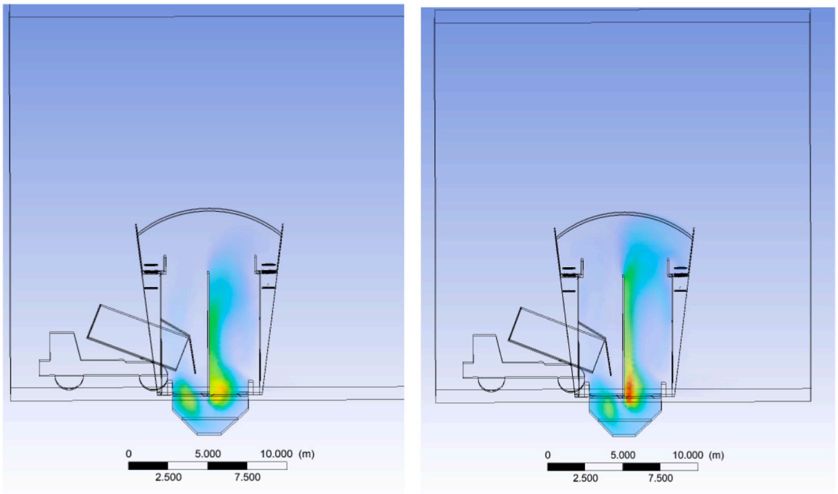
In order to better explore the movement law of dust in the cover body under the action of fans and inner sail, researchers conducted an in-depth analysis of the movement process of dusty gas in the unloading process.

The opposite wind of 5 m/s is set as the parameter condition of ambient wind, and the wind condition of downwind boundary is set for the negative pressure fan. A complete truck unloading cycle is simulated to obtain the distribution of flow field and movement trajectory of dusty airflow. The distribution of dusty gas flow field is shown in Fig. 8(a–d), and the movement track of dusty gas is shown in Fig. 9.

According to the analysis of Fig. 8, when the ambient wind is blocked by the inner sail, no convection wind is formed inside the cover body. And the dusty gas enters the cover body and continuously bounces back along the unloading pit to form vortex whose center appears at the bottom of the inner sail. In the unloading process, the dusty gas rises along the bottom edge of the pit after it is produced. Under the action of the auxiliary pressure of induced fans, the movement trend of the dusty gas escaping to unloading door is weakened. And the dusty gas flow turns inward and is basically trapped inside the cover body for circulating cleaning. The simulation results verify that the dust suppression effect of the optimized dust suppression cover is significantly improved from the perspective of microscopic gas movement.



（a）unloading process in the 3s （b）unloading process in the 10s



（c）unloading process in the 20s （d）unloading process in the 30s

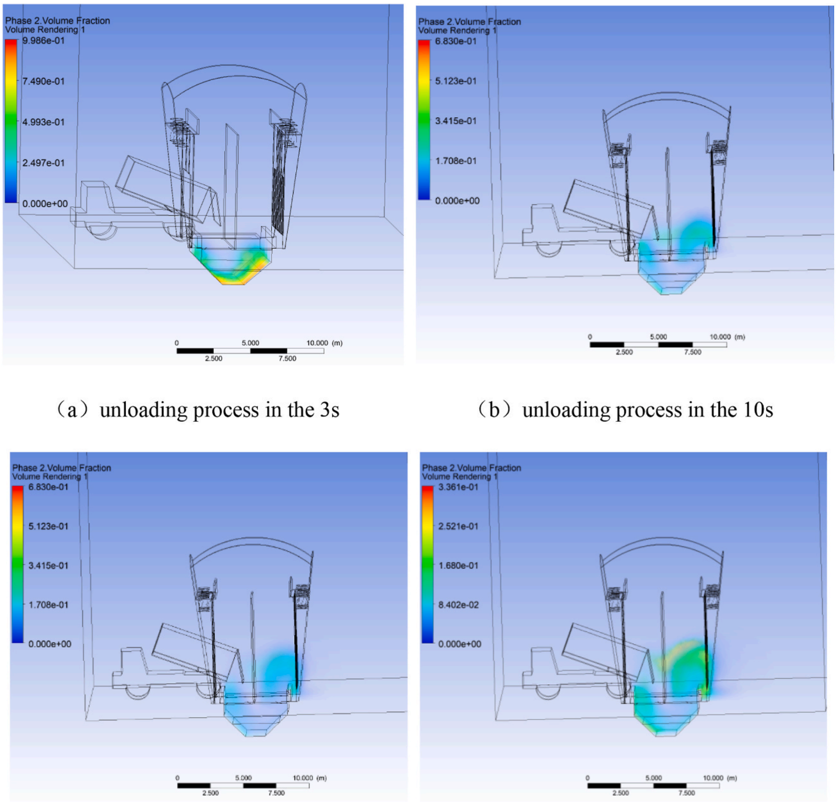
Fig. 7. The distribution of flow field under static wind condition.

As shown in Fig. 9, vector arrows represent the movement direction of dusty gas. Dusty gas moves to the bottom of the unloading pit with the material flow, and is continuously rebounded by the wall surface and drawn by the fan to form a closed-loop vortex. The greater the wind speed at the fan outlet, the more vortex lines. In addition, due to the obstruction of the middle inner sail, there is no streamline in the center area of the cover body, and the dusty gas form a closed-loop vortex line bypasses the inner sail. The structure of eddy current at the outlet of the fan is complex, and most of the air flow moves upward in reverse direction. It is due to that the dusty gas moves along the strong wind flow and bounces off when touching unloading plate. It can be found that the movement track of dusty gas basically appears inside the cover body, indicating that the optimized structure of the device has a good effect of dust suppression.

3.3. Application of optimizing engineering

The simulation results show that the dust suppression device can achieve better dust suppression effect after structure optimization. The researchers carried out practical engineering application research on the optimization of measures and transformed the induced air volume according to the principle of similarity. The transformation formula is as follows (equations [1–3]) :

$$V = \frac{G \times 3600}{\rho T} \tag{1}$$



（a）unloading process in the 3s （b）unloading process in the 10s

（c）unloading process in the 20s （d）unloading process in the 30s

Fig. 8. The distribution of dusty gas flow field.

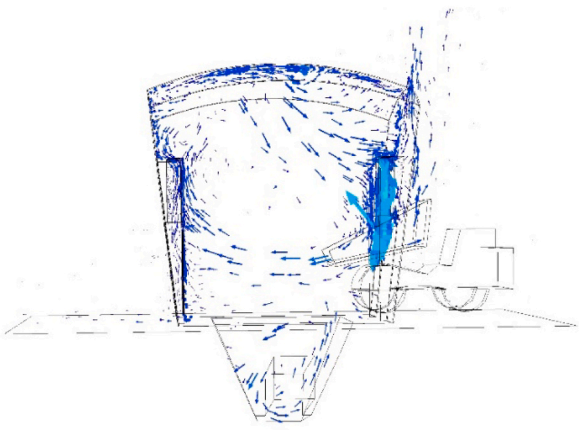


Fig. 9. The movement track of dusty gas.

$$\boldsymbol{Q} = kV \tag{2}$$

$$\frac{Q_1}{Q_0} = \frac{G_1 \times 3600}{\rho T_1} \Big/ \frac{G_0 \times 3600}{\rho T_0} \tag{3}$$

where, V is volume flow rate of materials, m^3/h; Q is the induced gas flow, m^3/h; G is material quantity, ton/time; T is the unloading time, s; ρ is the material packing density, ton/m^3; K is a constant.

After calculation, considering 10% surplus coefficient, the air volume of each fan is 6848–10271 m^3/h. A total of six explosion-proof and dust-proof fans were selected in this project, and three of those were set above the discharge port.

After overall optimization of the inner sail and fan of the field engineering device in accordance with the practical application research, the dust suppression effect of the dust suppression cover was tested in operation. It is found that the dust suppression effect is obviously better. The field application is shown in Fig. 10 below (see Fig. 2).

At the same time, the dust concentration around the field engineering application device before and after optimization was monitored and compared. The monitoring points were set at 0 m, 2 m, 5 m and 10 m away from the device on both sides of the unloading road, and 1.8 m away from the ground horizontally. The arrangement of monitoring points is shown in Fig. 11 below. The monitoring results are shown in Fig. 12.

The monitoring results show that the dust concentration around the optimized device is significantly lower than that before optimization. The lowest dust concentration around the optimized device is 19.52 mg/m^3 before optimization, while the lowest concentration around the optimized device can reach 0.31 mg/m^3 after optimization. It is worth noting that the dust concentration on the east side of the dust suppression cover is higher than that on the west side, especially before the optimization of the device. This is the result of the influence of external wind conditions. In the monitoring process, the west wind has been blowing, and the wind speed is relatively high. It can be found that the device optimization ameliorates the phenomenon of high dust concentration on the west side to a certain extent and weakens the influence of external wind conditions on the movement trend of dusty gases.

Moreover, the dust concentration around the optimized dust suppression cover (within 10 m) meets the restriction requirements of the Coal Industry Pollutant Discharge Standard. And the dust suppression effect of the optimized dust suppression cover meets the environmental protection regulations.

In summary, the results of field monitoring and simulation confirm that the dust suppression effect of the optimized dust suppression cover is significantly improved. For another, the dust is basically controlled inside the cover body during unloading and the dust concentration around the device meets the environmental protection requirements.

4. Conclusion

This study mainly explores the movement change and diffusion distribution of dust inside the cover through numerical simulation, so as to guide the application and optimization of dust suppression cover and obtain the following conclusions.

(1) Numerical simulation is a powerful tool to explore the microscopic motion law of fluid. Through the microscopic simulation analysis of the movement track and diffusion distribution of dusty gas in the unloading process, this research found that the dusty gas is squeezed and then bounces around and forms eddy current trend in the cover body under the action of pressure difference after the material falls to the bottom of the pit. Then, a new type of dust suppression device, micro-dynamic induction dust suppression cover was proposed. The device induces dusty gas to circulate in the way of pressure balance and closed-loop circulation to complete self-cleaning of dust. In the practical application process, the influence of external environmental factors and its own working conditions should be taken into account.

(2) The researchers optimized the design of the dust suppression cover by means of simulation. Simulation results showed that the optimization of the device can block the interference of the vortex movement caused by the ambient wind forming a draft inside the cover, and enhance the potential energy of the upward movement of the dust containing gas vortex, which improved the effect of dust suppression induced by device closure. However, the research and application of simulation in this study is mainly reflected in the microscopic gas movement, ignoring the meteorological influence of temperature and precipitation conditions on dust movement in practical application, which is also the limitation of numerical simulation.

(3) After technical demonstration, the optimized dust suppression cover is transformed and applied to the engineering project. Field monitoring results showed that the dust concentration around the optimized device is greatly reduced, and the influence of external wind conditions on the movement trend of dusty gas is weakened. The dust was basically trapped inside the device for circulating cleaning movement, and the dust suppression effect met the requirements of environmental protection.

Fig. 10. The situation of field application.

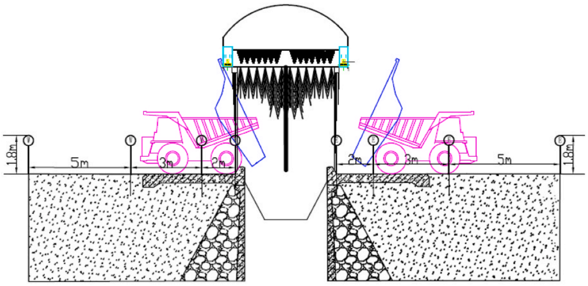


Fig. 11. Field monitoring point.

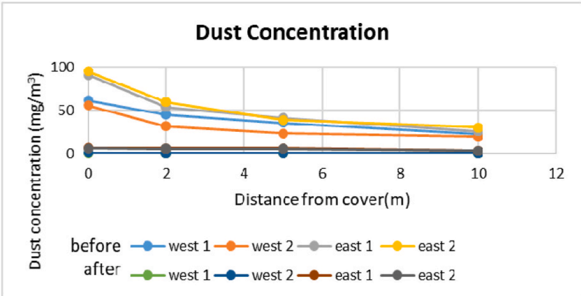


Fig. 12. Monitoring results of dust concentration.

Data availability statement

The data associated with the study hasn't been deposited into a publicly available repository. The data that has been used is confidential.

Author contribution statement

Tong Wu: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.
Zhuo Yang: Conceived and designed the experiments; Wrote the paper.
Kai Zhang: Performed the experiments; Analyzed and interpreted the data.
Bo Wang: Performed the experiments; Contributed reagents, materials, analysis tools or data.

Additional information

Supplementary content related to this article has been published online at [URL].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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