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Research Article

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Numerical Simulation Study on Dust Migration Law under Different Wind Speed

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Abstract: At present, it is very common to use ventilation to remove dust and dust at home and abroad. However, the influence of different wind speeds on dust migration is also different, and the effect of dust removal is also different. Therefore, it is necessary to study the influence of wind speed on dust migration. Gambit model and Fluent are used to carry out numerical simulation of dust movement in fully mechanized mining face, and the influence law of different wind speeds on dust migration in the face was found. The results show that airflow has a significant impact on dust movement. The dust concentration is relatively high near the coal cutter roller and the coal wall during coal cutting. Increasing the wind speed reduces the dust concentration near the coal cutter roller. During the ventilation and dust removal process, a wind speed around 1.5 m/s is considered the optimal wind speed for dust control.

Keywords: numerical simulation; wind speed; dust movement regularity

1. Introduction

The majority of coal mines in China operate using underground mining methods. During the coal extraction process, large amounts of coal dust, rock dust, and mixed dust are generated. In addition to these, occupational hazards such as noise, toxic and harmful substances, hydrogeological conditions, and meteorological factors also pose significant risks to the physical and mental health of underground workers. Among these hazards, the most serious are the various degrees of pneumoconiosis and silicosis caused by dust exposure. Following that are poisoning and heatstroke caused by toxic gases, as well as hearing loss or impairment resulting from noise exposure [1][2]. Despite persistent efforts to address these hazards over time, no fundamental solution has been reached. These risks continue to seriously threaten the health of coal miners and disrupt normal mining operations. Among all the hazards, dust poses the most significant threat, making it imperative to find solutions to dust-related issues.

Dust refers to coal dust, rock dust, and other toxic or harmful particulates, collectively known as mine dust. From a colloidal chemistry perspective, dust is an aerosol suspended in the air, with air as the dispersing medium and solid particles as the dispersed phase, forming a dispersed system [3]. Whether in underground or open-pit mining, large quantities of dust are generated, all of which pose risks to workers. However, underground mining is particularly hazardous due to the confined working space, which facilitates the accumulation of dust, leading to high concentrations. The dust concentration ratios at various operation points are shown in Table 1[4].

Table 1: Scale of dust production at each operation point of mine

Location of Operation Points	Dust Production Ratio
Dust production at the coal mining face	45%~80%
Dust production at the development face	20%~38%

Dust production at the bolting and spraying operation points	10%~15%
Dust production at the migration ventilation tunnels	5%~10%
Dust production at other operation points	2%~5%

As shown in Table 1, the coal mining face has the highest dust production among all operation points. Therefore, it is crucial to focus on dust control and prevention at the coal mining face.

The dust at the fully mechanized mining face primarily originates from the process of coal cutting by the shearer roller. Scholars both domestically and internationally have focused on studying dust migration patterns and dust concentrations at the dust generation sources. Currently, three methods are used to study dust migration patterns at specific coal mining faces: on-site measurements, laboratory experiments, and numerical simulation studies. The study of dust migration patterns essentially aims at identifying the most optimized dust removal and suppression methods. Currently, dust control and suppression technologies are well-developed both domestically and internationally. The most efficient dust removal methods, in terms of economic feasibility and dust removal efficiency, are summarized in Table 2[5]. Among these methods, ventilation-based dust removal is the most commonly applied. However, the impact of wind speed on dust migration varies, leading to different dust suppression outcomes. Therefore, it is essential to investigate the effect of wind speed on dust migration.

Table 2: Summary of dust removal methods

Method	Principle	Description
Wet Dust Removal	Utilizes the property of water's wettability, where dust absorbs moisture upon contact with water, thereby increasing its mass and enabling rapid sedimentation.	When dust comes into contact with water, it absorbs moisture, increasing its mass and causing rapid sedimentation. The wet dust removal method can be applied in many stages of coal mining production, typically during drilling and blasting operations, where water is injected into the hole bottom and rock fissures. This helps to wet, wash, and carry out dust particles, thus reducing dust generation at the source.
Purified Airflow	Dust-laden air from the working face is drawn into a purification airflow device that captures particulate matter.	Multiple spraying devices are systematically installed on the tunnel ceiling and water pipes to form a water curtain, which acts as a barrier. The dust-laden air passes through the water curtain, significantly reducing the dust concentration. The dust removal device directly filters the airflow, captures dust, and discharges clean air.
Physicochemical Dust Suppression	Adding dust suppressants to water is an effective physicochemical dust removal method, which evolved from the wet dust removal technique.	Fine particulate dust is difficult to capture with regular water mist due to the high surface tension of water, which makes it challenging to bind with small dust particles. The addition of dust suppressants reduces the surface tension of water, thereby improving its efficiency in capturing small particles.
Personal Protection	The last line of defense to prevent dust from entering the human respiratory system.	Common dust protection equipment worn by workers includes dust masks, dust caps, and dust respirators. These devices prevent dust from entering the respiratory system while not affecting work efficiency, and are widely used.
Ventilation Dust Removal	Utilizes the airflow in tunnels to carry the dust dispersed in the air out of the working face, improving the working environment.	Ventilation dust removal is a key component of the comprehensive dust suppression system in underground mines, which includes both local and full-area ventilation. Types include single extraction, single injection, and mixed long-pressure short-extraction ventilation methods. Underground, dust collectors are

mainly used to capture dust in the ventilation ducts.

2. Methodology

Establishment of the Geometrical Model

The main mechanical equipment in the fully mechanized mining face includes the coal shearer, hydraulic supports, cable trays, and so on. The layout of the fully mechanized mining face is not a regular geometric shape, and the installation of some electromechanical equipment is extremely complex. Therefore, accurately drawing the geometric model of the mining face is very challenging. It is thus essential to simplify some of the equipment on the mining face. The specific simplifications made are as follows:

(1) The effect of the motion of the coal shearer, hydraulic supports, conveyor belts, and other electromechanical equipment on the airflow in the mining face is ignored.

(2) Only the coal shearer's coal cutting section and the regions near the upwind and downwind directions are selected as the research area, specifically the region starting 4 meters upwind of the shearer's front roller and extending 25 meters behind it. This area is treated as a regular rectangular prism.

(3) Due to the complex structure of the coal shearer, it is necessary to simplify its design significantly. The body of the shearer is treated as a regular rectangular prism, the rocker arm is simplified as a combination of a rectangular prism and a cylinder, and the roller is simplified as a truncated cone.

(4) The cable tray is simplified as a regular rectangular prism.

(5) The hydraulic supports are directly simplified as individual cylindrical bodies, with the top beams and bases treated as planar boundaries. To ensure the quality of the mesh, the spacing between the hydraulic supports is adjusted to 1.5 meters.

After simplification, the dimensions of each part are shown in Table 3. According to the size table for each part, the dimensions of the upwind coal cutting face are shown in Figure 1.

Table 3: Simplified size table for each part

Dimensions	Length	Width	Height
Inlet section	4m	3.4m	3.2m
Cutting section	21m	4.1m	3.2m
Coal shearer body	7m	1.3m	1.4m
Cable tray	25m	0.3m	0.7m
Cutter roller	Diameter:1.8m; Cutting depth:0.7m		
Single hydraulic support	Diameter:0.3m; Height: 3.2m		

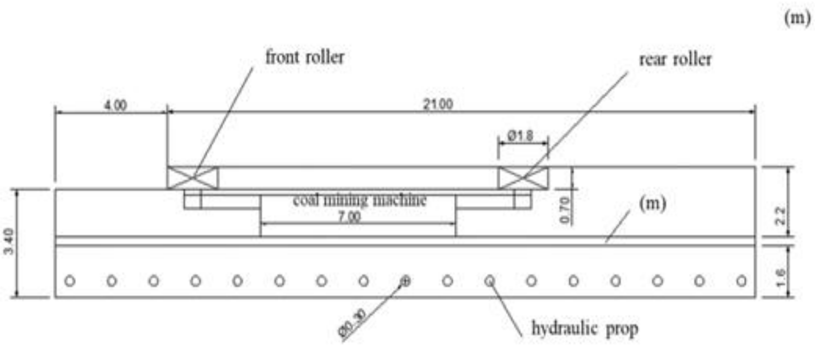


Figure 1: Size diagram of Top view of fully mechanized face

This paper primarily investigates the dust migration patterns on the top-view cross-section at a height of 1.5m, which corresponds to the approximate face height of mining workers in the mine. Therefore, a simplified model of the studied face is established using Gambit. Mesh generation is a crucial step in Fluent numerical simulations, as the size of the discretization error is directly related to the grid division. The larger the grid cell size, the greater the resulting error. However, if the grid is divided too finely, the number of cells increases substantially, which consumes significant computational resources and results in longer simulation times. Therefore, it is essential to choose an appropriate grid size. In this study, the grid cells used for the division of the working face are square-shaped, with a total of 10,209 grid cells in the top-view cross-section

Numerical Simulation Parameters and Boundary Condition Settings

After importing the mesh generated in Gambit into Fluent, it is necessary to configure the computational model, boundary conditions, and computational parameters. The specific settings are as follows:

(1) Boundary Condition Setup

In this model, the coal shearer roller, body, and coal wall are all set as wall boundaries. Only the coal shearer roller has its DPM boundary type set to "Escape," while the other components are set to "Trap." The working face inlet is defined as a velocity inlet boundary condition, and the working face outlet is set as a free outflow boundary. The coal shearer roller is designated as a dust source.

The actual ventilation velocity for the mining face under investigation in this study is 1.5 m/s. To explore the influence of varying wind speeds, we selected two velocities both below and above the actual ventilation speed. Accordingly, the inlet velocities were set to 0.7 m/s, 1.1 m/s, 1.5 m/s, 1.9 m/s, and 2.3 m/s, encompassing a range of five different wind speeds. This setup aims to investigate the dust migration patterns at the mining face under different ventilation conditions and to identify the optimal wind speed for effective ventilation and dust control.

(2) Discrete Phase Model Parameters Configuration

This study investigates the dust migration patterns in the coal mining face. The parameters for the Discrete Phase Model and the dust source parameters are outlined in Table 4.

Table 4: Discrete phase parameter settings

Discrete phase parameter settings		**Dust source parameters**	
discrete phase model	**Parameter setting**	**Injection**	**parameter setting**
Interaction With Continuous Phase	ON	Injection Type	Surface
Update DPM Sources Every Flow Iteration	ON	Particle Type	Inert
Number of Continuous Phase Iteration Per DPM Iteration	20	Material	Coal-hv
Max Number of Steps	500	Min Diameter; Max Diameter; Mean Diameter	1×10^{-6} m; 0.0001 m; 1×10^{-5} m
Length Scale（m）	0.01	Spread parameter	1.13
Drag Law	Spherical	Total Flow Rate	0.013

3. Results and Analysis

This study focuses on modeling and simulation of the top view section at a height of 1.5m. Given that the primary objective is to investigate the impact of ventilation speed on dust migration patterns in the mining face, wind speed is considered as the independent variable. The study examines five distinct wind speeds: 0.7 m/s, 1.1 m/s, 1.5 m/s, 1.9 m/s, and 2.3 m/s [6]. The specific simulation results are presented as follows.

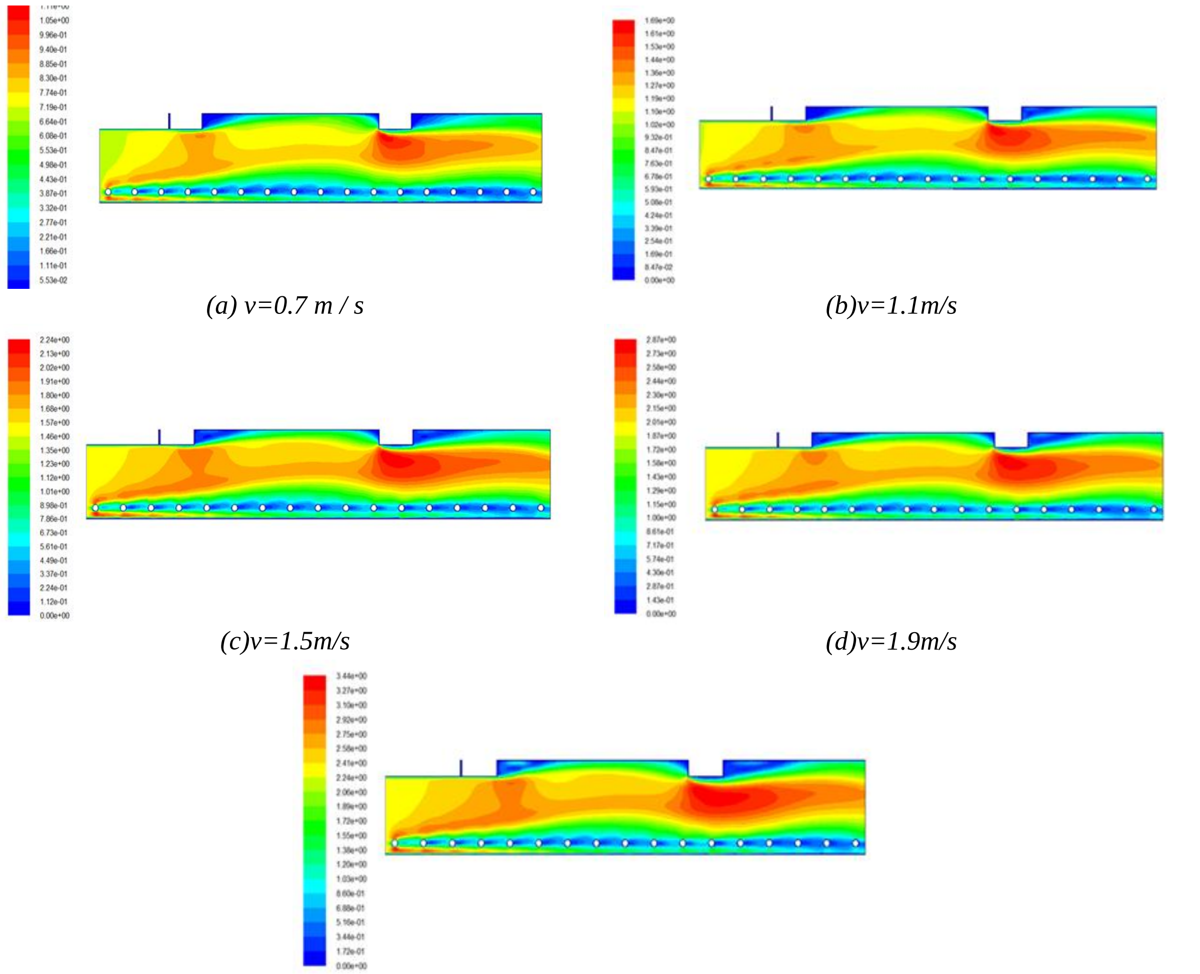
Analysis of the Flow Field Characteristics in the Mining Face under Varying Wind Speed Conditions

The simulation results indicate that at an inlet wind speed of 0.7 m/s, a slight accumulation of airflow occurs at the front roller of the shearer. Moreover, a pronounced vortex phenomenon is observed at the front end of the shearer's rear roller, where the wind speed reaches its maximum value of approximately 1.1 m/s.

When the inlet velocity is 1.1 m/s, the area of vortex formation in the airflow is larger compared to the range observed at an inlet velocity of 0.7 m/s, with the maximum wind speed reaching approximately 1.69 m/s.

When the inlet velocity is 1.5 m/s, the airflow distribution map shows a significant reduction in the areas with wind speeds around 0 m/s, compared to the regions with inlet velocities of 0.7 m/s and 1.1 m/s.

When the inlet wind speed increases to 1.9 m/s, the airflow distribution diagram shows that only a small portion of the area has a wind speed of approximately 0 m/s, indicating that airflow barely passes through this region. When the inlet wind speed is 2.3 m/s, the airflow distribution map at the top view section shows that only a small area behind the obstacles is unaffected by the airflow, while the remaining areas experience airflow.



(a) v=0.7 m / s *(b)v=1.1m/s*

(c)v=1.5m/s *(d)v=1.9m/s*

(e)v=2.3m/s

Figure 2: wind flow field distribution

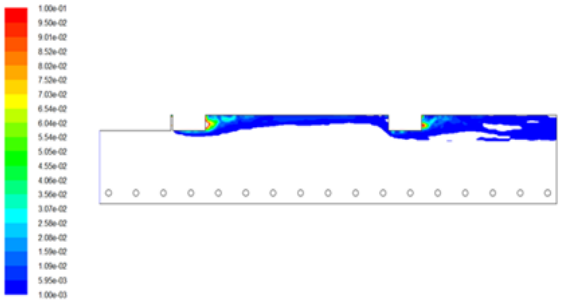
From the airflow distribution maps in Figure 2, it can be seen that as the inlet wind speed increases, the area affected by airflow gradually expands, while the region with a wind speed of 0 m/s progressively decreases. In the airflow distribution maps, it is evident that the wind speed increases near the coal cutter roller, particularly at the rear of the cutter roller, where the wind speed increases significantly, making it the region with the highest wind speed in the airflow field.

Analysis of Dust Concentration Distribution Characteristics under Different Wind Speeds in the Fully Mechanized Mining Face

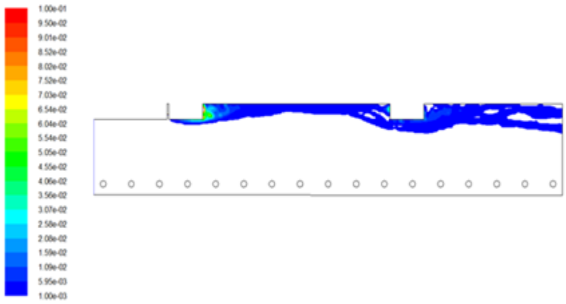
The simulation results indicate that when the wind speed is 0.7 m/s, the dust concentration is highest near the coal cutter's roller. The dust distribution map shows that the dust particles move in the direction of the airflow towards the outlet. However, due to the proximity between the front roller and the coal wall, the airflow cannot penetrate into this gap, resulting in an excessively high dust concentration in this area. This accumulation of dust is primarily caused by the limited airflow that is unable to reach certain regions, leaving the dust trapped in these spaces.

Based on the simulation results, when the wind speed is 1.1 m/s, the airflow is able to carry the dust out to the designated dust discharge point. The dust concentration near the coal cutter's roller has significantly decreased

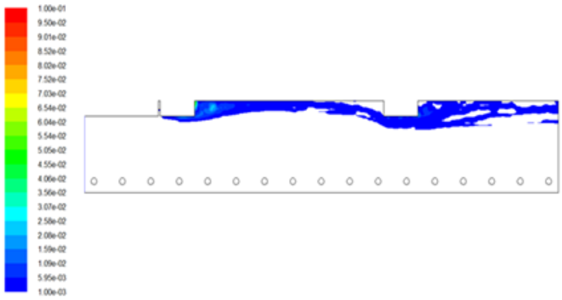
compared to when the wind speed was 0.7 m/s. This indicates that a wind speed of 0.7 m/s is too low for effective ventilation and dust removal in this working face, resulting in an excessively high dust concentration.
The simulation results indicate that when the wind speed is 1.5 m/s, the dust concentration is significantly lower. Even near the coal cutter's roller, the dust concentration is almost entirely below 0.007 kg/m³.
The simulation results show that as the wind speed increases, the range of dust distribution decreases. At a wind speed of 1.9 m/s, the dust concentration in most areas is below 0.05 kg/m³.
At a wind speed of 2.3 m/s, the dust concentration is relatively low, with most concentrations remaining below 0.05 kg/m³. The dispersion area of the dust is also relatively small.
The analysis above shows that as the inlet wind speed gradually increases, both the dust concentration and the range of dust dispersion decrease. This suggests that higher wind speeds result in more effective ventilation and dust removal. However, it is important to consider that there are underground workers present in the mining face, and the wind speed can affect their working conditions. Additionally, as the wind speed increases, so do the ventilation costs. Therefore, it is not feasible to rely on unlimited increases in wind speed to achieve the best ventilation and dust removal effect. Instead, the optimal wind speed for ventilation must be selected. It should also be noted that ventilation and dust removal cannot eliminate dust from all areas. Regardless of the wind speed, dust remains concentrated primarily near the coal shearer drum, particularly beneath the drum and in the gap between the front drum and the coal wall. This indicates that, when implementing other dust control and removal measures for the fully mechanized mining face, particular attention should be paid to these areas, as ventilation and dust removal alone are not fully effective in removing dust from these regions.



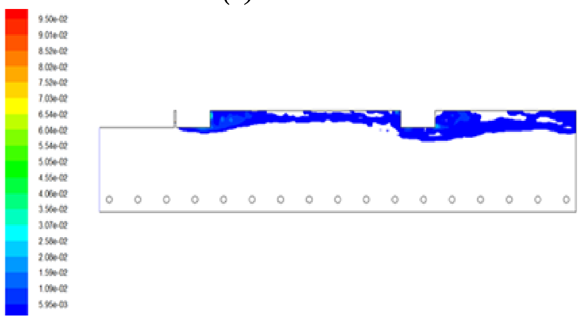
(a) v=0.7 m / s



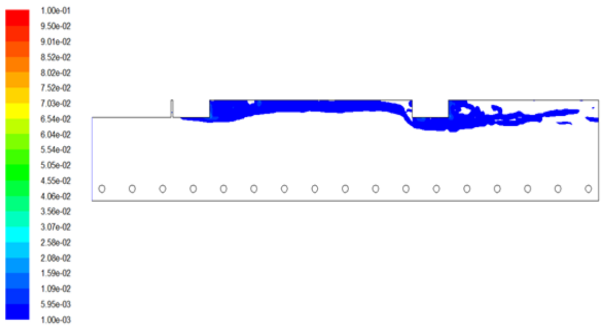
(b)v=1.1m/s



(c)v=1.5m/s



(d)v=1.9m/s



(e)v=2.3m/s

Figure 3: Dust distribution under different wind speeds

4. Conclusion

This study focuses on the coal mining face, using theories from fluid mechanics and numerical simulation. A simulation model for the top-view cross-section of the mining face at a height of 1.5 meters is developed. Numerical simulations are then conducted using Fluent software, and the results are analyzed. The main findings of the study are as follows:

(1) The dust concentration is relatively high near the coal cutter roller and the coal wall during coal cutting, with the dust content near the front roller of the coal shearer significantly higher than that near the rear roller. This is primarily because there is only a small gap between the front roller of the coal shearer and the coal wall, which hinders the airflow in this area. As a result, a large amount of dust accumulates here, causing the dust concentration to be higher than in other areas.

(2) The simulation results show that airflow has a significant impact on dust movement. When the wind speed is v = 0.7 m/s, a large amount of dust accumulates near the coal cutter roller. However, as the wind speed increases to v = 1.1 m/s, the dust concentration near the coal cutter roller decreases significantly. When the wind speed further increases from v = 1.1 m/s to v = 1.5 m/s, the dust concentration continues to decrease. This indicates that as the inlet wind speed gradually increases, the dust concentration progressively decreases.

(3) Increasing the wind speed reduces the dust concentration near the coal cutter roller. From v = 0.7 m/s to v = 1.5 m/s, it is evident that as the wind speed increases, the dust concentration gradually decreases, and the change in dust content is quite noticeable. However, from v = 1.5 m/s to v = 2.3 m/s, although the dust concentration continues to decrease, the effect of the change in dust content is less pronounced. This suggests that during the ventilation and dust removal process, when the wind speed is below 1.5 m/s, wind speed is the most significant factor affecting the effectiveness of dust control. Once the wind speed exceeds 1.5 m/s, wind speed is no longer the primary factor influencing dust removal efficiency.

(4) During the ventilation and dust removal process, a wind speed around 1.5 m/s is considered the optimal wind speed for dust control. Although the dust removal effect at 1.5 m/s is not the most efficient, increasing the wind speed further does not result in a significantly noticeable reduction in dust concentration. Considering economic factors, a wind speed around 1.5 m/s is the optimal ventilation and dust removal speed for this fully mechanized mining face.

(5) Ventilation and dust removal can reduce dust concentration in most areas, but it cannot eliminate dust in all locations. In some specific areas (such as near the front roller of the coal shearer), alternative methods are required to effectively reduce the dust concentration in those regions.

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