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A Systematic Review of Coal Mine Dust Suppression Methods Based on Numerical Simulations and Experimental Investigations

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Abstract

Large quantities of dust are generated during coal mining and transportation, posing a threat to workers' health. Therefore, this article conducts a systematic review of the literature on coal mine dedusting. This study examines coal mine dust suppression methods by integrating numerical simulations and experiments, focusing on four aspects: the structural improvement of the dust remover, chemical modification, the optimization of the operating environment, and the ventilation system. The structural improvement of a dust remover primarily involves optimizing the nozzle's structure and size, particularly the Laval structure. The findings indicate that alterations in the surface structure of the Laval nozzle's contraction section have minimal effect on the airflow velocity. Chemical modification of the dust remover can enhance the wetting properties of coal dust and includes non-phytochemical and phytochemical modification. Molecular Dynamics (MD) simulations are frequently employed in chemical modification. The optimization of the operating environment for dust removers focuses predominantly on spray pressure optimization.

Keywords: coal mine, dust suppression, structural improvement, chemical modification, operating environment

1. Introduction

Dust generated during coal mining and processing is called coal mine dust. It primarily comprises coal particles, rock fragments, and ore powders produced during coal pulverizing, conveying, loading, and transportation. The size range of these dust particles is expansive, ranging from visible large particles to microscopic fine particles [1]. Coal is the primary component of coal mine dust, containing other chemical elements such as silica, iron, aluminum, calcium, and magnesium. In addition, coal mine dust may contain hazardous minerals, including silica, sulfur dioxide, and heavy metals [2].

Dust remains suspended in mines and coal processing facilities, contaminating the working environment and posing health risks to miners. Fine coal mine dust particles can even reach the deepest regions of the lungs via the respiratory system. Long-term exposure to coal mine pollution makes miners susceptible to respiratory diseases like pneumoconiosis and chronic bronchitis [3]. Moreover, coal dust is highly combustible and can easily ignite upon contact with a fire source, leading to explosions. It also reduces visibility in the workplace, increasing the risk of accidents. Additionally, coal dust accelerates equipment wear and tear, compromising operational safety. High concentrations of coal dust can cause air pollution, throat

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irritation, and contamination of clothing, further diminishing the overall working experience. According to the "2023 China Health and Medical Development Statistical Bulletin" released by the National Health Commission, Fig. 1 displays the number of new pneumoconiosis patients from 2013 to 2023 [4]. The data indicate a declining trend in recent years, reflecting notable improvements in the dust removal effectiveness of coal mines. However, the issue of coal dust should not be underestimated.

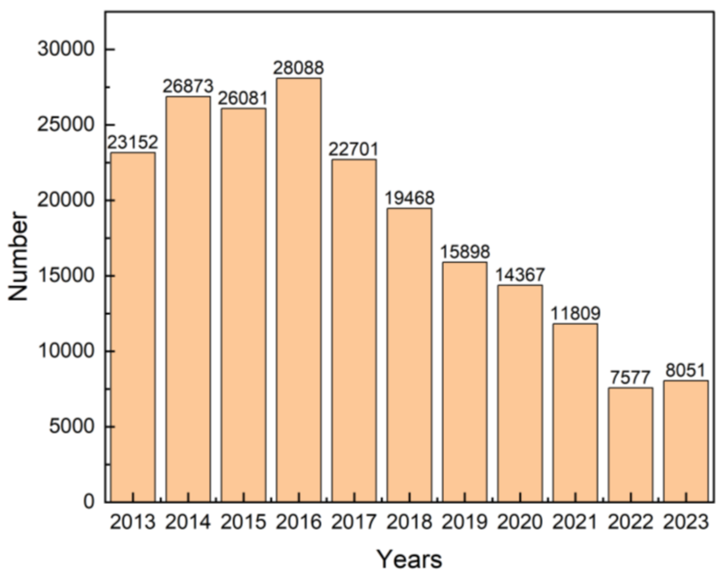


Fig. 1 The number of new pneumoconiosis patients from 2013 to 2023 [4]

Numerical simulation and experimental research have become two primary and complementary methods in coal mine dust control, enabling a more comprehensive understanding and optimization of related technologies. This paper aims to comprehensively evaluate the application of numerical simulation and experimental research in coal mine dust suppression and compare the characteristics of various dust removal methods.

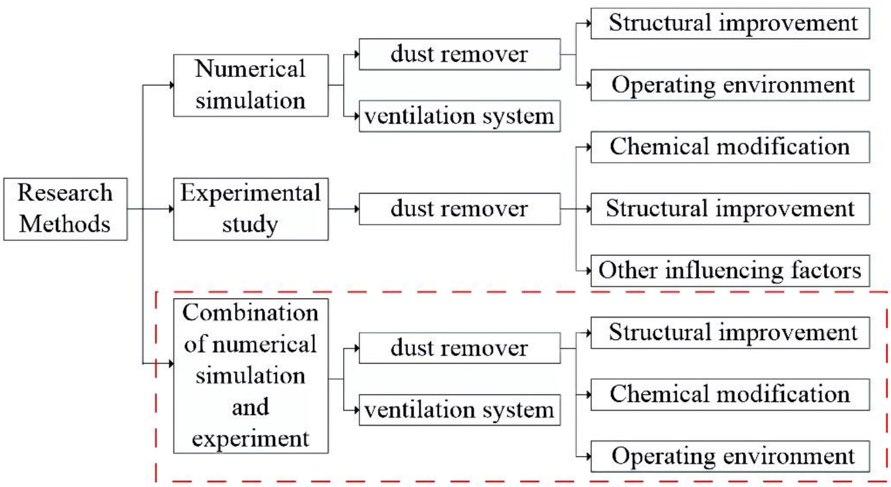
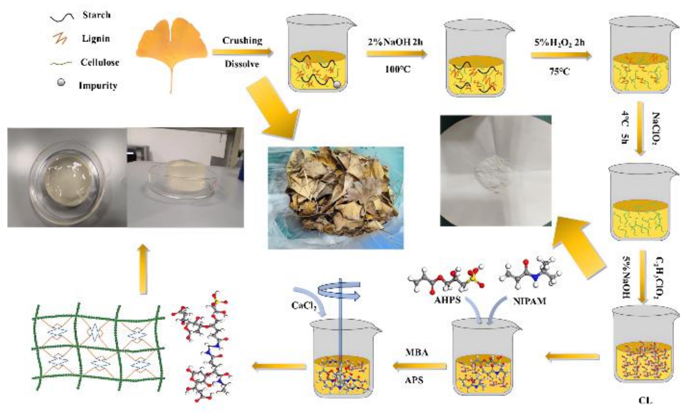
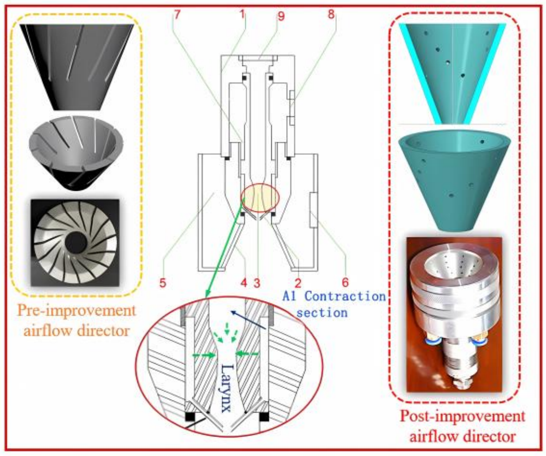


Fig. 2 A summary of the improvement of dust removal technology [5]

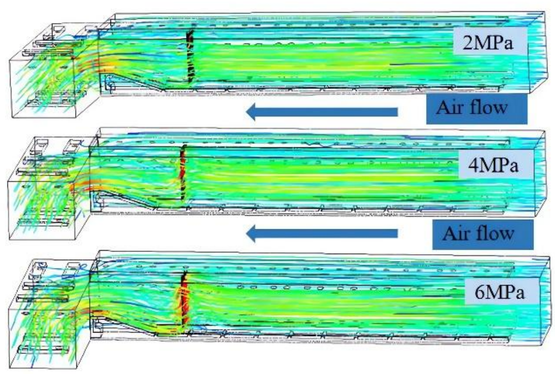
Dust removers and ventilation systems are utilized to control coal mine pollution. As depicted in Fig. 2, improvements in dust removal technology have been summarized through a comprehensive literature review [5]. Based on different coal mine dust control technologies, dust removal methods can be further categorized into the following four types: structural improvement of dust remover, chemical modification, optimization of the operating environment, and the ventilation system, as illustrated in Fig. 3. Ventilation system dust removal can achieve large-scale air purification. Structural improvement of the dust remover can directly improve the performance of the dust removal device. Chemical modification of the dust remover can significantly increase dust removal efficiency. The optimization of dust removers in the operating environment can help save energy [6-9].



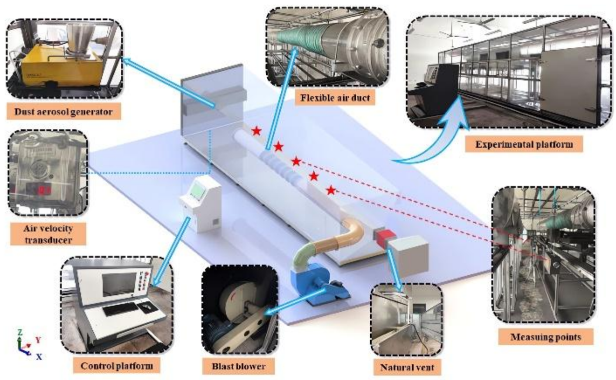
(a) Chemical modification of the dust remover



(b) Structural improvement of the dust remover



(c) Operating environment optimization of the dust remover



(d) Ventilation system

Fig. 3 Four methods of dust removal [6-9]

The objective of the study was accomplished through the resolution of the following questions:

- What methods are used to remove dust in coal mines when combining numerical simulation with experiments?
- What are the characteristics of these dust removal methods, and which parameters are primarily studied?
- What are the current research trends in coal mine dust removal, and how does the surface structure modification of the Laval nozzle shrinkage section affect airflow velocity?

2. Optimization of Coal Mine Dust Remover and Ventilation

Dust removal in coal mines mainly includes four methods: structural improvement of the dust remover, chemical modification, optimization of the operating environment, and improvement of the ventilation system. The following is a review of the research content and main findings of each dust removal method.

2.1. Structural improvement of the dust remover

The improvement of the dust remover structure by numerical simulation and experiment focuses primarily on the nozzle, fan, atomization points, and blowing, especially the nozzle structure and size. Table 1 summarizes the papers on the structural improvement of dust removers by numerical simulation and experiment.

Table 1 Structural improvement of dust removers

Reference	Object	Numerical simulation	Experimental study	Main finding
Yin et al. [15]	Multi-stage atomization external spray with dust removal fan	(Fluent; Standard k-ε model) Airflow-dust field distribution; Fog droplet field distribution	(a phase Doppler laser interferometer (PDI)) Nozzle atomization characteristics	The total dust reduction rate is 87.12%
Peng et al. [12]	An air-assisted PM10 control device	(Fluent; Realizable k-ε model) The optimal selection of nozzles; Droplet diameter, concentration, and velocity parameters; Airflow migration	(PDI) The optimal choice of nozzles; Droplet diameter, concentration, and velocity parameters	The optimal pressure is 8 MPa; The dust control rate is above 90%
Peng et al. [10]	A novel wind-assisted centralized spraying dedusting device	(Fluent; Realizable k-ε model) Droplet concentration distribution; Spraying pressure; Opening of the pneumatic motor	(PDI) Macroscopic parameters (Spray pressure, atomizing angle); Microscopic parameters (Droplet concentration distribution)	The dust removal rate around the coal cutter driver reaches 87.96%
Zhang et al. [14]	Supersonic antigravity nozzle	(COMSOL Multiphysics software version 5.4; Spalart–Allmaras) Comparing injection through a probe and injection through a hole; Particle size; Particle velocity	(High-speed cameras) Comparing injection through a probe and injection through a hole; Spray angle	Dust isolation efficiency can reach 94.07% and save more energy
Peng et al. [13]	Roadway full-section water curtain device	(Fluent; Realizable k-ε model) Airflow and spray field distribution	(PDI) Flow rate, atomizing angle, and range	The settling rate of PM2.5 is 95.7%
Zhai et al. [17]	Ejector precipitator	(Fluent; Standard k–ε model) Pressure distribution; Velocity distribution; Liquid-gas ratio	(3D particle dynamic analyzer) Measurement of macroscopic parameters and microscopic parameters; Dust removal efficiency; Liquid-gas ratio	Removal ratios of total coal dust: 89.5%; Removal ratios of respirable coal dust: 91.0%
Ma et al. [16]	A coal cutter external spraying device	(Fluent; Realizable k-ε model) Characteristics of the spray fields (Droplet concentration, droplet diameter)	(PDI) Optimization of nozzles; Spray field macro-parameters	2.4 mm nozzle caliber with 8 MPa spraying pressure; Dust suppression efficiency around the driver is 90.33%
Peng et al. [11]	Blowing spraying synergistic dust removal technology	(Fluent; Realizable k-ε model) Spray field concentration; Spray-distribution nephogram	(PDI) Macro characteristics (Spray flow shape, Atomization angle, Flow rate); Mesoscopic data (Spray field concentration)	The dust removal rate around the driver is 90.3%
Nie et al. [18]	A new wind-assisted spray device	(Fluent; Realizable k-ε model) Spray field concentration; Droplet size	(PDI) Macroscopic characteristics (Atomization angle, effective range, nozzle flow rate); Microscopic parameters (Spray field concentration, droplet size)	Total dust removal efficiency around the driver is 88.31%; Respirable dust removal efficiency is 83.45%
Ren et al. [7]	An innovative vortex atomizing nozzle	(COMSOL; Kelvin-Helmholtz) Airflow field; Droplet size distribution; Droplet velocity distribution	(Particle size analyzer) Wind resistance and distribution uniformity; Spray particle size	A reduction in coal dust concentration exceeding 90%
Nie et al. [8]	A wet dust catcher on the hydraulic support	(Fluent; Realizable k-ε model) Particle mass concentration; Droplet size	(PDI) Particle mass concentration; Droplet size	The dust removal rate of the shearer driver reached 86.20 %

Peng et al. [10] developed a new wind-assisted centralized spraying dedusting device for dust control. The novel device enabled the spraying field to be more precisely focused on the source of dust production. The optimal operating pressure was determined through numerical simulation, experiment, and field measurement. It is possible to achieve a particulate suppression rate of 87.96% around the coal cutter's driver. Similarly, Peng et al. investigated synergistic blowing-spraying 10th removal technology installed on hydraulic support. The technology enabled the formation of a high-quality spray and wind curtain, and the dust suppression rate from the driver's position reached its highest at 90.3%, significantly enhancing the dust removal effect.

Taking PM10 and PM2.5 into account, Peng et al. [12] designed an air-assisted PM10 control device for the drum-cutting procedure. The optimal nozzle type and pressure were determined using experiments and numerical simulations. Field measurements indicate that the control rate for PM10 surpasses 90%. Besides, Peng et al. [13] investigated the full-section water curtain device for preventing PM2.5 diffusion pollution. The spray parameters were optimized using Fluent simulation and experiment. Field measurements indicate that the PM2.5 settlement rate was as high as 95.7%. Adequate PM2.5 respirable dust settlement was achieved.

Most researchers use Fluent software for structural simulation of dust collectors, while others use COMSOL. COMSOL is a simulation software for multi-physical modeling based on finite element analysis (FEA). It enables engineers and scientists to construct multi-physical models on a single, unified platform and perform simulation analysis of coupling and interaction. Zhang et al. [14] designed a new nozzle by combining the existing supersonic aerodynamic atomization nozzles with a Laval nozzle and a probe structure. They compared two water injection methods, injection through a probe and perforation, using COMSOL. In conjunction with the experiment, it was discovered that the new nozzle had a larger atomizing angle, smaller atomizing particle size, more significant energy savings, and the ability to achieve anti-gravity water absorption. In the sphere of dust removal, it is the first time particles have been broken using supersonic gas, and the rate has reached 94.07%. Ren et al. [7] also used COMSOL to study an innovative vortex atomizing nozzle, with a dust removal efficiency of over 90%.

On the other hand, Yin et al. and Ma et al. explored the external spray systems of shearers. Yin et al. [15] designed a multi-stage atomization with a fan for the shearer. The efficiency is reaching 80%. Similarly, Ma et al. [16] investigated the nozzle types of a coal cutter external spraying device and optimized the nozzle calibers.

However, Zhai et al. and Nie et al. utilized negative pressure suction of dust-laden air flow [17-18]. Zhai et al. [17] designed an ejector precipitator. They optimized the nozzle's parameters and the ratio of liquid to gas. As determined by field measurements, the removal ratios for respirable coal dust and total coal dust were 91.0% and 89.5%, respectively, with respirable coal dust attaining a higher dust removal efficiency than total dust. Its significance in the removal of respirable particles is substantial.

Similarly, Nie et al. [18] conducted a study on a wind-assisted spray device. They integrated macroscopic and microscopic aspects. The Fluent software was used to simulate microscopic parameters such as spray field concentration and droplet size. The experiments focused on the macroscopic characteristics of the spray field, including atomization angle, effective range, and nozzle flow rate, as well as microscopic parameters such as spray field concentration and droplet size. Nie et al. [8] also studied a wet dust catcher on hydraulic support, with the dust removal rate of the shearer driver reaching 86.20%.

In previous research, macroscopic parameters, such as atomization Angle and spray range, and microscopic parameters, such as particle size, were used to examine spray field characteristics. After analysis, the average efficiency reported in the above studies is approximately 90%. Numerical analysis commonly employs the k-ε model, while experiments often use a phase Doppler laser interferometer for measurements. Most existing studies focus on dust concentration and removal efficiency around the driver, as seen in the works of Peng et al. [12], Ma et al. [16], Peng et al. [11], and Nie et al. [18]. To better protect all miners, expanding the research scope to include other positions in the working environment is recommended.

2.2. Laval nozzle design for dust remover

(1) Laval nozzle application status

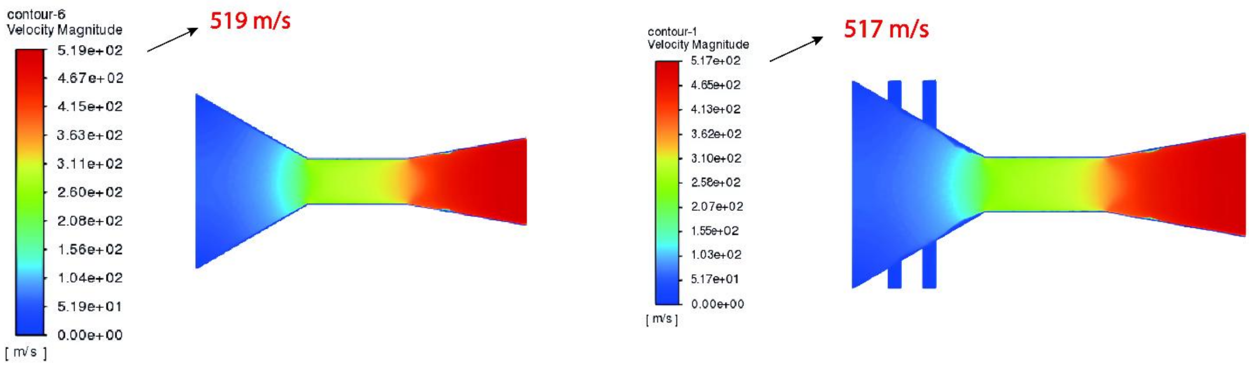
The Laval nozzle is a specially designed nozzle that comprises three components: the contraction section, the throat section, and the expansion section. Laval nozzles are specifically engineered to increase the velocity of high-pressure gases to achieve supersonic speeds. The Laval nozzle is widely used in various fields, such as rocket propulsion systems, metallurgy, internal combustion engine oil atomization, and natural gas dehydration. However, more studies are needed on Laval nozzles for coal mine dust removal, particularly when combined with numerical simulations and experiments.

Zhang et al. [19-20] studied a supersonic antigravity siphon atomization nozzle. COMSOL software was employed to simulate the process of droplet crushing and atomization. The results show that the new nozzles surpass the traditional atomizing nozzles in droplet velocity, water conservation, pressure conservation, range, and attenuation Angle.

Furthermore, Zhang et al. [14] studied a supersonic antigravity nozzle based on the Laval nozzle and probe jet. The results of their research indicate that a supersonic atomization probe nozzle has better atomization performance. However, these studies did not delve into the specifics of the nozzle’s structure and size, leaving room for further exploration. Due to its excellent atomization capabilities, the Laval nozzle is a potential research avenue for coal mine dust removal.

(2) Numerical simulation of Laval nozzle

Fig. 4 (a) displays the flow of a Laval nozzle. By examining the velocity cloud image, it is evident that the flow velocity at the inlet of the Laval nozzle is low, increases at the contraction section, and reaches the sonic speed at the throat. The speed continues to grow during the expansion phase, reaching supersonic speeds. Fig. 4 (b) shows a numerical simulation of the flow of the Laval nozzle with structural changes in the contraction section. All other conditions remain unchanged. The simulation findings indicate a marginal decrease in airflow velocity, from 519 m/s to 517 m/s, with a mere decrement of 2 m/s. The results indicate that changes in the surface structure of the contraction section of the Laval nozzle have a minimal impact on airflow velocity.



(a) Laval nozzle flow

(b) Laval nozzle with structural changes in the contraction section

Fig. 4 Numerical simulation of Laval nozzle

2.3. Chemical modification of the dust remover

Numerous researchers utilized numerical simulation and experimentation to make a chemical modification of a dust remover. Table 2 summarizes the papers on the chemical modification of dust removers by numerical simulation and experiment. Fluent software was initially used to simulate dust trajectory, airflow, airflow-dust, and other parameters.

Table 2 Chemical modification of dust removers

Reference	Object	Numerical simulation	Experimental study	Main finding
Xi et al. [21]	A Foam-sol foaming device	(Fluent) Dust trajectory	Compare the efficiency of dust removal using water, aqueous foam, and foam-sol	Symmetric whirlpools manifested beneath the inlet, featuring a maximum diameter of 0.52 meters for the most enormous vortex; Foaming is multiplied by 30 times;
Bao et al. [22]	A novel hydrogel based on crosslinked polymers	(Fluent) Airflow simulation for wind erosion test; Airflow-dust simulation	Wettability; Water retention; Wind erosion resistance; Thermogravimetric analysis; SEM morphology observation	Dust suppression gel exhibits twice the wettability to coal dust as water does; Dust suppression gel has excellent wind erosion resistance; Dust suppression gels reduced coal dust concentration by around 90% compared to water sprinkling
Yuan et al. [23]	Non-ionic surfactant AEO9	(MD) Motion process of water, AEO9, and lignite system	Wettability; Evaporation rate of coal; Contact angle	AEO9 can be effectively adsorbed onto the surface of coal and improve the hydrophilicity of lignite
Niu et al. [24]	Lauryl glucoside (APG-12) molecules	(MD) Dynamic behavior of surfactant molecules on the surface of coal molecules; Electrostatic potential; Surface charge	Wettability tests	APG-12 can adsorb onto the coal surface and attract water molecules via hydrogen bonding
Ren et al. [27]	AA-DM-CNF/CA dust-suppressing microcapsules	(MD) Microscopic action mechanism of AA-DM-CNF/CA dust suppressing microcapsules	Product performance tests (Adaptability test, dust suppression rate test, weather resistance test, degradability test, and synergistic combustion test)	Good dust suppression, weather resistance, degradation, and synergistic combustion performance
Ji et al. [25]	SDS and JFC composite ratios	(MD) Different composite ratios of SDS and JFC surfactant	Wettability tests; Contact angle; Surface tension; Aggregation ability	With the increase of JFC concentration in the compound solution, the contact angle and surface tension exhibit a decrease; JFC improved the aggregation ability between coal dust; 1:3 (SDS/JFC) mixing ratio
Gao et al. [26]	A new wetting agent	(MD) Micro-wetting mechanism of coal dust	Coal dust settling behavior; Contact angles; Zeta potential on the coal surface	Effectively improve the wettability; Dust removal rate of 89%
Xu et al. [28]	A modified starch-based low-viscosity and high-consolidation foam dust suppressant	(MD-Materials Studio 8.0) Adsorption structure; Mean square displacement (MSD)	Foaming ability and wettability; Viscosity and hardness; Structure characterization; Contact angle and surface tension; N2 adsorption experiment; Scanning electron microscope; Dust suppression rate	High consolidation and low viscosity; Dust suppression rate of 98.17% for PM10

For example, Xi et al. [21] researched a foam-sol foaming device. Fluent was used to simulate the particulate trajectory. Experiments were conducted to compare the dust removal efficiency of water, aqueous foam, and foam-sol. The results indicated that the foam-sol was more effective than other agents at removing dust. Likewise, Bao et al. [22] created a novel hydrogel based on crosslinked polymers. The results demonstrated that the dust suppression gel possessed water retention properties, water-saving properties, and exceptional resistance to wind erosion. Its effectiveness exceeds 9 times that of water spray.

Due to chemical reactions during the process of chemical modification and the need to comprehend the dynamic behavior of molecules, researchers later widely adopted molecular dynamics simulations. During simulation, empirical potential functions or models based on physical principles can be used to characterize the forces and energies associated with particle interactions. The positions, velocities, kinetic energies, potential energies, and interactions between particles can all be determined through molecular dynamics simulations. By introducing external fields or altering the initial state of particles within the simulation, it is possible to study the dynamic behavior, structural evolution, thermodynamic properties, and more of the system. MD simulations have numerous applications in chemistry, physics, and materials science. They can be used to study chemical reactions, material properties, protein folding, fluid flow, and other processes. It is possible to acquire details and dynamic information that may be difficult to observe experimentally through simulations, which aids in interpreting experimental phenomena, guides experimental design, and optimizes material performance.

The objects of experiments and simulations involving molecular dynamics (MD) include surfactants, wetting agents, and dust suppressants. Yuan et al. [23] investigated the impact of the non-ionic surfactant AEO9 on the adsorption and hydration of lignite. They utilized MD simulation to simulate the motion process of the water/AEO9/lignite system and tested wettability, the evaporation rate of coal, and contact angle by experiment. Similarly, Niu et al. [24] examined the microscopic mechanism of lauryl glucoside wetting coal dust. They applied MD simulation to study the dynamic behavior, which contained electrostatic potential and surface charge. Experiments were conducted to evaluate wettability. The results showed that APG-12 could adsorb onto coal surfaces and attract water molecules via hydrogen bonding.

Furthermore, Ji et al. [25] investigated SDS (Sodium dodecyl sulfate)/JFC (Fatty alcohol polyoxyethylene ether) surfactant. They used MD simulation to demonstrate the microscopic characteristics of water molecules. Experiments were conducted to evaluate wettability, contact angle, surface tension, and aggregation ability.

On the other hand, Gao et al. [26] prepared a new wetting agent. They analyzed the micro-wetting mechanism of coal dust using MD simulation. The results demonstrated that a novel wetting agent enhanced wettability, with an 89% particulate removal rate.

In addition, Ren et al. [27] presented a novel insight. They extracted cellulose nanofibrils (CNF) from peanut shells, created a new capsule core dust suppressant form, and used calcium alginate to create self-adaptive microcapsules. The microscopic action mechanism of AA-DM-CNF/CA dust-suppressing microcapsules was investigated using MD simulation, and product performance was evaluated experimentally. The capsule core and wall worked together to suppress dust, extending the dust suppression time. Moreover, Xu et al. [28] utilized tapioca starch as a raw material and combined it with foam to create a foam dust suppressant with low viscosity and consolidated coal dust. The MD simulation software examined the adsorption structure and mean square displacement (MSD). Experiments were conducted to determine foaming ability, wettability, viscosity, hardness, structure characterization, etc. The findings indicated that the rate of PM10 particulate suppression was 98.17 %. The combination of foams and plants is particularly effective at removing dust. In this regard, additional research is anticipated.

In 2024, many studies have combined experiments and numerical simulations on chemical modification. Han et al. [29] studied the wetting effect of the dust suppression reagent solutions on coal dust. Yu et al. [30] employed graft copolymerization modification and compounding techniques to develop a composite dust suppressant for mining applications. Liu et al. [31] integrated macroscopic experiments, mesoscopic characterization, and microscopic simulations to investigate the impact of three novel ionic liquids on the wettability of coal dust surfaces.

At the same time, Ren et al. [6] developed a cost-effective, eco-friendly, and high-performance coal dust suppressant using carboxymethyl ginkgo cellulose extracted and modified from Ginkgo biloba leaves, achieving a dust suppression efficiency of 93%. Based on the green and environmentally friendly method of enzyme crosslinking, Dong et al. [32] prepared an eco-friendly composite dust suppression foam by modifying soy protein isolates (SPI) with enzyme crosslinked gelatin (GEL) molecules, achieving a dust suppression efficiency of 98%. Liu et al. [33] selected four structurally similar ethoxy-containing surfactants to prepare solutions at varying concentrations to choose high-quality and efficient water-based materials. Wang et al. [34] developed a GEL-GG/OB-2 foam dust suppressant with a highly polymerized reticulate structure, using polymer bio-based materials, gelatin (GEL), and guar gum (GG), as the main components for the Maillard reaction. The dust suppression efficiency reached 98.2%.

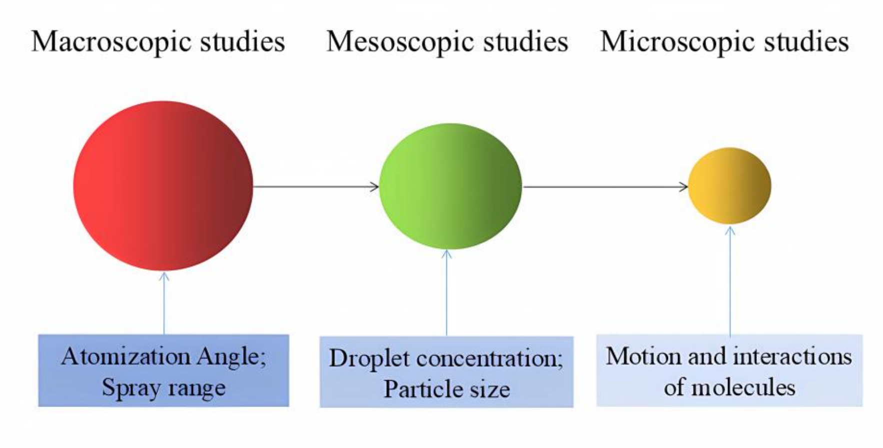


Fig. 5 Changes in research parameters

According to the above paper, research on coal mine dust removal has progressed from macroscopic studies to mesoscopic studies and then to microscopic studies. Changes in research parameters are shown in Fig. 5. The mesoscopic parameters refer to droplet concentration and particle size, which were discussed as microscopic parameters in the section on structural enhancement. From CFD (Fluent) to MD, the true nature of microscopic research has become apparent, which allows simulation objects to include the motion and interactions of molecules in addition to coal dust trajectories, airflow, droplet motion, electrostatic charges, and surface charges. Experiments primarily examine the following parameters: efficiency, wettability, contact angle, surface tension, water retention, resistance to wind erosion, adaptability, weather resistance, degradability, synergistic combustion, evaporation rate, aggregation ability, zeta potential on the coal surface, foaming ability, viscosity, and hardness. Based on the reported values in the literature, the average dust suppression efficiency is approximately 94%.

2.4. Operating environment optimization of the dust remover

This section describes the numerical simulation and experimental optimization of the operational environment of a dust remover. Table 3 provides a summary of the papers on the optimization of the operating environment of dust removers by numerical simulation and experiment. The primary influencing factors include spray pressure, installation angle of the nozzle, droplet diameter, magnetization, etc.

Table 3 Operating environment optimization of dust removers

Reference	Influence factor	Main finding
Wang et al. [35]	Volume-flow rate ratio γ_f; The velocity ratio of droplets to dust γ_v	Dedusting efficiency $\eta_f = 11.846\ln(\gamma_f) + 30.375$, R2= 0.9745; Dedusting efficiency $\eta_v = -0.0819\ \gamma_v^3 + 1.2102\ \gamma_v^2 - 2.4142\ \gamma_v + 54.451$, $R^2 = 0.974$
Peng et al. [12]	Spraying pressure	A spraying pressure of 8 MPa
Yang et al. [36]	Spraying pressure of the external spraying system; Installation angle of nozzles	Spray pressure of 8 MPa; Installation angle of nozzles of 30°
Wang et al. [41]	Air supply pressure of the internal-mixing air-assisted atomizing nozzle	Water pressure of 0.5 MPa
Han et al. [42]	Water supply pressure of the internal mixing air atomizing nozzle	Air pressure of 0.5 MPa; Water pressure of 0.6 MPa.
Yu et al. [37]	Spray pressure of the two optimal spray schemes	Gravity-driven supply of water: 2.0-4 MPa; Utilizing a booster pump: 2.0-8 MPa
Ma et al. [16]	Spraying pressure of a coal cutter external spraying device	The pressure is 8 MPa
Nie et al. [38]	Spray pressure of a new wind-assisted negative pressure spray device; Installation angle of spray device; Air output	The spray pressure of 6 MPa; The spray device deviates by 30°; Air output is 90 L/min
Xu et al. [40]	Droplets under different particle size ratios; Different initial droplet velocities	Particle size ratio of $\theta \geq 2$; Droplets' initial velocity is 20 m/s
Wang et al. [43]	Magnetization of Magnetized Water Spray	Magnetic field intensity is 150 mT; Magnetization time is 80 s

Wang et al. [35] investigated respirable dust's turbulent aggregation and deposition mechanisms during wet dedusting. They proposed a mathematical model for the wet dedusting process and derived dedusting efficiency calculation formulas. Similarly, Yang et al. [36] and Ma et al. [16] explored an external spraying system for a coal cutter. They obtained the optimized values of 8 MPa for spraying pressure and 30° for the installation angle of nozzles.

Besides, Peng et al. [12] determined that 8 MPa is the optimal value for spraying pressure. Similarly, Yu et al. [37] presented two optimal dust suppression spray schemes. The initial plan, 2.0-4 MPa, used a gravity-driven water supply. The second strategy, 2.0-8 MPa, utilized a booster pump. Furthermore, Nie et al. [8, 38-39] studied wind-assisted spray devices and determined that the optimal spray pressures were 6 MPa and 5 MPa, achieving average dust suppression efficiencies of 91.05% and 85%, respectively.

Specifically, Xu et al. [40] used Fluent to simulate the dynamic wetting process of coal dust with spray droplets. Fluent was used to study the micro-scale collision process between droplets and dust particles, which differs from the MD simulation of the motion and interactions of molecular systems described in the previous chapter.

On the other hand, Wang et al. [41] and Han et al. [42] investigated the internal-mixing air-assisted atomizing nozzle. Both the air and water supply pressures were optimized. They obtained values of approximately 0.5 MPa for both water and air supply pressure. Differently, Wang et al. [43] analyzed magnetized water spray. The dust removal efficacy is optimized with a magnetic field intensity of 150 mT and a magnetization time of 80 seconds.

In conclusion, most studies have focused on optimizing spray pressure. Yang et al. [36] and Ma et al. [16] optimized the spray pressure for the external spraying system of the coal cutter at 8 MPa. Nie et al. [38] achieved a spray pressure of 6 MPa for their wind-assisted spray. Yu et al. [37] proposed gravity-driven spray schemes with a 2-4 MPa pressure. Consequently, when the wind assists, spray pressure tends to decrease. Wang et al. [41] and Han et al. [42] studied internal-mixing air-assisted atomization, achieving a spray pressure of only around 0.5 MPa, thereby substantially lowering the spray pressure. Xu et al. utilized Fluent to simulate intermolecular collisions. Meanwhile, MD simulation provides a powerful tool for analyzing the motion and interactions within molecular systems. Opting for MD simulation could potentially yield higher accuracy. Based on the studies above, optimizing the operating environment of the dust remover can achieve an efficiency of approximately 88% [37].

2.5. Ventilation system optimization

Some scholars have optimized ventilation systems. Li et al. [44-45] conducted experimental studies and Fluent simulations on wall-mounted swirling ventilation, achieving a dust suppression efficiency of 92.14%. Similarly, Wei et al. [46] researched ventilation in an underground coal mine using a Fluent simulation and experiment. On the other hand, Hua et al. [47] studied an effective ventilation system with a 3D spiral wind-curtain generator through Fluent simulation and experiment. However, Jing et al. [48] investigated an innovative vortex-blowing suction dust control technology through COMSOL simulations and experiments. By optimizing the blowing-suction methods and ratios, they achieved a dust suppression efficiency of 93.25%. Zheng et al. [9] studied the distribution of the airflow field in the roadway and the spatial-temporal evolution of dust pollution under forced ventilation conditions. Ren et al. [49] developed a novel Vortex Air Flow Negative Pressure Entrainment Dust Removal Device, achieving a dust removal efficiency of up to 90%. Based on the aforementioned studies, the dust removal efficiency of ventilation systems is approximately 92%.

Based on previous studies, it can be concluded that only a few researchers integrate numerical simulations with laboratory experiments in ventilation system research, primarily due to the challenges associated with constructing experimental platforms. Furthermore, the current level of automation in ventilation systems remains suboptimal, with many still relying on manual intervention, leading to reduced efficiency and increased safety risks. Some scholars have already made significant contributions in this field. Nie et al. [50] developed a portable, high-precision dual-wavelength dust sensor specifically for mining applications to overcome the limitations of existing coal mine respirable dust detectors, such as low-concentration detection inaccuracy and poor stability. However, China’s automatic inspection technology for coal mine dust removal and ventilation dust control is still in the development and improvement stage.

3. Discussion and Results

The key keywords in this review are “coal mine,” “Numerical Simulation and Experiments,” “dust removal,” and “dust suppression.” To ensure a comprehensive and reproducible review, a systematic literature collection was conducted on coal mine dust removal research. The collected studies span from 2019 to 2024 and include only English-language publications. The following scientific indexing databases were utilized: Web of Science, ScienceDirect, IEEE Xplore, and Scopus. There are 14 articles on the chemical modification of dust removers, 11 articles on the structural improvement of dust removers, 12 articles on the optimization of the operating environment, and 7 articles on ventilation systems, as shown in Fig. 6. The total number is 44. The proportion of each dust removal method is calculated by dividing the number of related articles by the total number, resulting in 31.8%, 25%, 27.3%, and 15.9%, respectively.

Based on the dust removal efficiency reported in the paper, the approximate efficiencies of the four methods are as follows: chemical modification of dust remover (94%), structural improvements of dust remover (90%), operating environment optimization of dust remover (88%), and ventilation systems (92%), as shown in Fig. 7. Among them, chemical modification achieves the highest efficiency. Structural improvement and ventilation systems are also highly effective, while operating environment optimization has the lowest efficiency. Bao et al. [22] tested the dust suppression effects of dust suppression gels and water at the fully mechanized mining face of Jinjitan Coal Mine. The results showed that spraying dust suppression gel was more than nine times more effective in suppressing coal dust compared to spraying water.

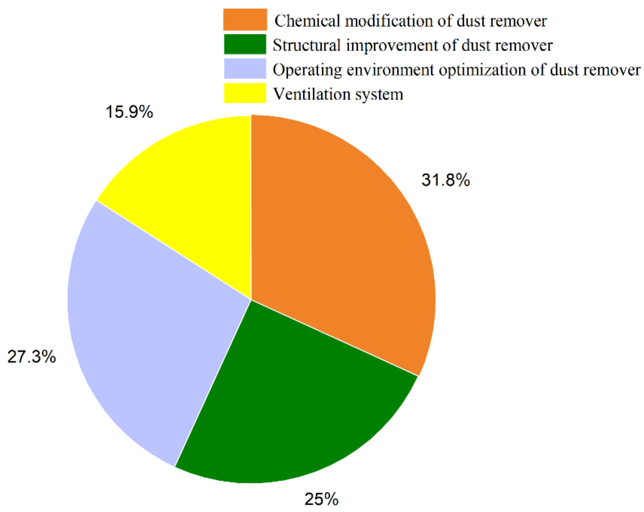


Fig. 6 Percentage of Publications on Four Dust Removal Methods Using Numerical Simulation and Experiments

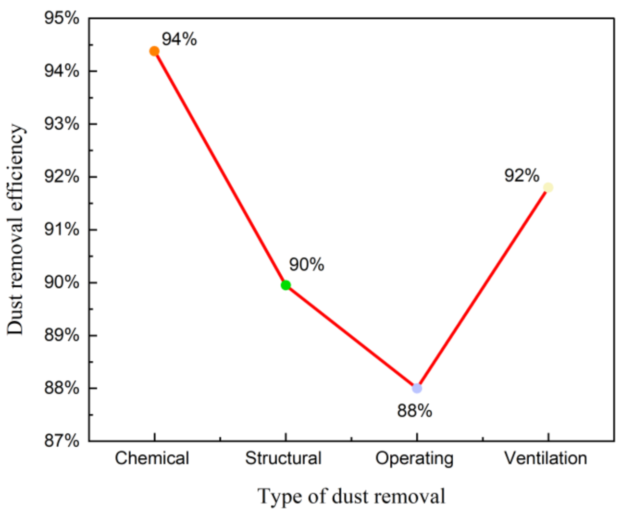


Fig. 7 A comparison of the dust removal efficiency of four methods

Among these, research on chemical modification of dust removers accounts for the most significant proportion. The annual publication trends, as shown in Fig. 8, reveal a steady increase in research on chemical modification methods. Studies on structural improvement and operating environment optimization were primarily concentrated in 2019 and 2020, while chemical modification emerged as a research focus in 2020 and has since gained significant traction, becoming the most widely studied method by 2024 [51-52].

Chemical modifications can be adapted to different operating conditions. For instance, specific dust suppression formulations can be selected for high-temperature, high-humidity, or low-temperature environments to enhance adaptability. Zhao et al. [53] investigated chlorine salt-based antifreeze road dust suppressants for open-pit coal mines, conducting tests at the Hebei Open-pit Coal Mine in Inner Mongolia. Their proprietary antifreeze dust suppressant achieves an impressively low freezing point of -36.4°C. Notably, its effective dust suppression duration is 150 times longer than water's, leading to a 53% reduction in dust suppression costs. Additionally, Dong et al. [32] studied a biodegradable dust suppression foam that can be applied in open-pit coal mines and tailings. This foam is biodegradable, eco-friendly, and sustainable.

Large coal mines can utilize biodegradable dust suppression foam, which quickly covers the coal pile surface, effectively preventing the spread of fine dust particles while being environmentally friendly and leaving no residue. For a fully mechanized coal mining face, water-based foam suppressants can be used to enhance the ability of water mist to encapsulate dust, reducing its dispersion. In low-temperature environments, antifreeze liquid dust suppressants are recommended to prevent freezing and ensure effective dust control. Given its low cost, high efficiency, broad applicability, and environmentally friendly nature, chemical modification is emerging as a key trend in future research [54].

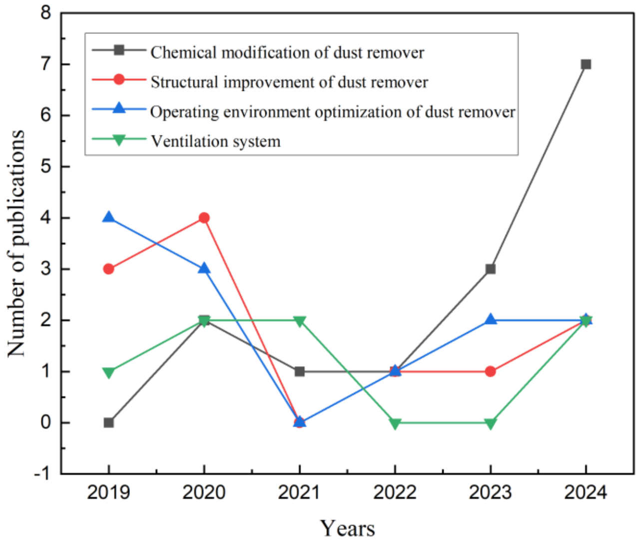


Fig. 8 Number of publications per year for the four methods in this review

Numerical simulation is an effective tool for predicting dust dispersion, optimizing ventilation systems, and evaluating dust suppression measures. However, its accuracy is limited by several factors, including the simplification of mathematical models that neglect complex effects like turbulence and particle interactions, inaccuracies in boundary and initial conditions such as airflow velocity, humidity, and coal dust concentration, numerical discretization errors where a coarse mesh loses detail while an overly fine mesh increases computational load, and computational resource constraints that necessitate simplifications of certain physical phenomena. Integrating numerical simulation with experimental methods enhances the reliability and accuracy of coal mine dust control research, as real-world experimental data can refine mathematical models, improve boundary conditions, apply localized mesh refinement in critical areas, and validate and correct simulation results for more effective dust control strategies [10-17].

Results and recommendations for future work:

(1) The structural improvement of a dust remover mainly focuses on optimizing the structure and dimensions of the nozzle, particularly by incorporating a Laval structure, which generates supersonic airflow and improves atomization efficiency. Further research is needed in this area, with more studies published to guide future investigations, particularly on ensuring the stability of supersonic airflow for enhanced dust suppression performance.

(2) Chemical modification of dust removers can enhance the wetting properties of coal dust, significantly improving dust suppression efficiency. This modification can be categorized into non-phytochemical and phytochemical approaches. Molecular Dynamics (MD) simulations are frequently utilized in this field to analyze atomic and molecular interactions, providing insights into particle formation, aggregation, motion, and deposition. Potential research directions for chemical modification in dust suppression include developing biodegradable suppressants, such as bio-based polymers, to minimize environmental pollution. Investigating low-toxicity and low-corrosive formulations, such as low-chloride salt suppressants, can help reduce their impact on equipment and ecosystems. Additionally, integrating intelligent monitoring systems, such as dust concentration sensors, can enable precise control of suppressant application, minimizing unnecessary chemical usage and enhancing overall efficiency.

(3) The optimization of the operating environment for dust removers primarily focuses on optimizing spray pressure. When wind assistance is used, spray pressure tends to decrease. In the case of internal-mixing air-assisted atomization, spray pressure can be reduced to around 0.5 MPa, significantly lowering the overall spray pressure.

(4) Optimization of ventilation involves refining both airflow and structural design. However, the automation level in this area still needs improvement. With the advancement of artificial intelligence technologies, intelligent monitoring and optimization are expected to become key research focuses. By leveraging real-time monitoring and data analysis, researchers can optimize the operating parameters and processes of dust collection systems, thereby enhancing energy efficiency and conserving resources.

The interdisciplinary integration of engineering, chemistry, and environmental science offers immense potential for developing more advanced dust suppression methods. Engineering plays a crucial role in optimizing ventilation systems, enhancing the efficiency of dust removal equipment, and using numerical simulations to accurately predict dust dispersion patterns. Chemistry contributes by developing novel dust suppressants, such as biodegradable dust suppression foams or low-corrosive, antifreeze dust control solutions, improving adaptability and environmental compatibility. Environmental science assesses the ecological impact of dust suppression technologies, ensuring compliance with sustainability requirements. By fostering interdisciplinary collaboration, advanced chemical formulations can be integrated with high-efficiency mechanical systems, while environmental science helps refine application strategies to minimize secondary pollution. This holistic approach not only enhances the precision and applicability of dust control measures but also promotes greener and safer coal mining practices, providing more scientific solutions for future mine site environmental management.

The standardization of dust suppression techniques is particularly crucial for the future. As coal mining operations expand and environmental regulations become increasingly stringent, unified standards can ensure that different mining sites implement consistent and effective dust control measures, safeguarding workers' health and safety. Standardization facilitates the selection of optimal technologies, improves dust suppression efficiency, minimizes resource waste and environmental pollution, and drives the industry toward greener, more sustainable development. Moreover, with the continuous emergence of new technologies, standardization promotes innovation and knowledge sharing, ensuring the reliability and applicability of novel methods. More importantly, it streamlines regulatory processes, aiding policy implementation and industry management. Therefore, establishing standardized dust suppression methods is key to achieving efficient, safe, and environmentally friendly coal mining operations.

4. Conclusion

In conclusion, integrating numerical simulation and experimentation plays a crucial role in optimizing coal mine dust control. This study demonstrates that altering the surface structure in the contraction section of the Laval nozzle has a minimal impact on airflow velocity. The chemical modification of dust removers can enhance the wetting properties of coal dust, thereby improving dust suppression efficiency. The Laval nozzle accelerates air to supersonic speeds, creating a greater velocity differential between the air and liquid phases, which makes the droplets easier to break apart. Due to these advantages, chemical modification and the Laval nozzle hold significant potential as promising directions for future coal mine dust removal technologies. Furthermore, the interdisciplinary integration of engineering, chemistry, and environmental science offers immense potential for developing more advanced dust suppression methods. The standardization of dust suppression techniques will also be crucial in the future.

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Conflicts of Interest

The authors declare no conflict of interest.

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