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Development of New Spray Dust Suppression Materials in Metal Mines and Prediction of Algorithm Simulation Effect

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Abstract

PROBLEM: Dust contamination in metal mining poses substantial dangers to environmental quality and human health. Modern mining operations cannot use traditional spray dust suppression methods because they are poorly adapted to changing climate conditions, low efficient, and detrimental to the environment.
INTRODUCTION: Dust pollution seriously impacts the environment and human health in metal mine operations. Traditional spray dust suppression technology has many problems, such as limited effect, environmental impact, and poor climate adaptability.
OBJECTIVES: The purpose of this article is to develop a new type of spray dust suppression material and predict its dust suppression effect through algorithm simulation. Firstly, efficient and environmentally friendly dust-reducing materials were screened, and after evaluating the dust-reducing effect under laboratory conditions, the optimal material combination was determined.
METHODS: Using computational fluid dynamics (CFD), a numerical model of the spray process was constructed to simulate the dust suppression effect of different materials under different climatic conditions.
RESULTS: The results show that the highest dust reduction efficiency of the new spray dust reduction material is more than 4.3% higher than that of the traditional material, and it shows good stability.
CONCLUSION: The new spray dust control material and its effect prediction method studied in this article provide an effective solution for dust control in metal mines, which has important theoretical value and practical application prospects.

Keywords: Spray Dust Suppression; Computational Fluid Dynamics; Metal Mining; Algorithm Simulation.

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1. Introduction

With the acceleration of industrialization, the problem of dust pollution in metal mines is becoming increasingly serious, becoming an important factor affecting environmental quality and human health. Due to the fast industrialization of mining, there is now more dust pollution in metal mines, which can harm human health and the environment. Conventional spray systems, usually water-based, have limits, environmental downsides, high operational costs, and struggle to manage tiny dust particles adequately. Although the traditional spray dust reduction technology reduces the dust concentration to a certain extent, its effect is limited by the characteristics of materials and environmental factors, and it is difficult to meet the increasingly stringent environmental requirements. Therefore, it is urgent to develop more efficient and environmentally friendly spray dust reduction materials and technical solutions to improve dust reduction efficiency and stability. The main contribution of this article is to systematically study the performance of various spray dust suppression materials, especially the potential of new polymer materials in dust suppression applications.

Polymer-based products are more stable in challenging mining settings because they have better dust-binding qualities, have longer-lasting effects, and are environmentally resistant. Compared to traditional techniques, their efficacy and lifespan can eventually result in lower operational expenses, particularly in labour and maintenance, despite their greater initial cost. Considerations like dust binding efficiency, durability, water retention, convenience of usage, environmental effect, cost and economic viability, and health and safety are considered while evaluating novel polymer materials for industrial dust suppression. Through the analysis and comparison of existing spray dust suppression technologies, a method based on the combination of physical simulation and CFD is proposed, and the dust suppression effects of different material combinations are deeply simulated and verified by experiments. In addition, this article also explores the performance of materials under different environmental conditions, providing a theoretical basis for subsequent material development.

The organizational structure of this article is as follows: In the relevant work part, the development status of spray dust suppression technology in the world is reviewed, and the necessity and urgency of research are clarified. Particle size distribution, material concentration, application technique, ambient conditions, and material composition all impact how successful dust control products are in metal mines. Their performance is also influenced by climatic factors, chemical and physical characteristics, and application techniques, including spraying and injection. Various criteria and metrics, including dust suppression efficiency, durability testing, adhesion and cohesion tests, and field experiments, are used to assess dust control compounds. These tests measure the dust present before and after suppression, test the durability of materials, and determine how well they work in mining conditions. The material research section describes the characteristics and experimental design of the selected spray dust suppression materials in detail. The effectiveness of materials used in spray dust suppression is greatly affected by humidity. Low humidity decreases efficiency and necessitates more frequent applications, but high moisture improves dust suppression by attaching dust particles and reducing water evaporation. Because humidity also influences droplet size and behaviour, humid environments are better for these materials. The CFD model construction section showcases the process of physical simulation and CFD model construction and the analysis of their results. The experiment part discusses the experimental results of new spray dust suppression materials and evaluates the user experience of different materials through a satisfaction survey. The conclusion summarizes the study's main findings and points out future research directions. The core problem to be solved in this article is optimizing the selection and application of spray dust suppression materials under different environmental conditions to improve dust suppression efficiency and stability. The innovation lies in adopting a comprehensive physical simulation and CFD technology scheme, combined with numerical simulation and experimental data, to systematically evaluate the effect and applicability of new spray dust suppression materials. The article hopes to provide a scientific basis and effective technical support for dust control in metal mines and contribute to environmental protection and sustainable development through this technical solution.

The rest of the paper is structured as follows: Section 2 shows related work; Section 3 describes material research; Section 4 explores CFD model construction; Section 5 depicts test experiments of new spray dust suppression material; Section 6 addresses the conclusion part.

2. Related Work

In recent years, many outstanding experts have researched and explored dust-reducing materials. Shan T prepared iron cobalt magnetic porous media based on foam nickel by electrodeposition under a magnetic field and used it as a dust collector in the electromagnetic dynamic dust removal system [1]. Bian S mainly discussed the application of new filter materials in the dust removal system of converter steelmaking [2]. Fan X developed a self-powered induction spray dedusting system because the dust concentration in the coal mine was too high to affect the safety of coal miners [3]. To study the nozzle parameters most suitable for spray dust removal, Yang H established a three-phase coupling model of air phase, dust phase and spray phase using the Euler Lagrange method [4]. Li X studied the influence of electrode materials and the size of electrostatic spray scrubber on the charge of water droplets and proposed the key factors to optimize the electrode design in the dust removal process [5]. When studying the performance of dust-reducing materials, their impact on the environment, including potential harm to ecosystems or sustainability, was not fully considered.

In addition, many people are researching the application of CFD. Vinuesa R pointed out that machine learning can effectively improve the accuracy and efficiency of CFD simulations, especially when dealing with complex flow phenomena [6]. Mani M reviewed the current technological advancements and emphasized the crucial role of CFD in designing and optimizing aircraft performance [7]. Nandiyanto A B D found that combining particle technology in CFD can improve the understanding of multiphase flow and promote the development of new materials and technologies [8]. Sidik N A C studied the correlation between CFD and nanotechnology and discussed the potential applications of CFD in nanofluid research and nanomaterial development [9]. Szpicer A addressed the application of CFD in the food industry, particularly its importance in optimizing food processing and packaging processes [10]. The selection of parameters in CFD simulations significantly impacts the results. Still, many studies have not conducted a sufficient sensitivity analysis, limiting the results' generalization ability. Harikumar N investigates how to improve geological big data analysis and decision-making through cloud computing and Geographic Information System (GIS) technology. It draws attention to issues with data management and offers fixes for better security, usability, and collaboration in areas including conservation, health research, and disaster management [11]. Sreekar P looks at the analysis of Gaussian data in cloud computing using K-means clustering. The findings demonstrate how cluster sizes may save costs by significantly influencing calculation time and accuracy. The study highlights the importance of managing resources wisely and selecting the ideal beginning points for effective clustering performance [12]. Raj K G, Early detection is essential for effectively treating acute lymphoblastic leukaemia (ALL), a deadly disease. They cannot identify small blood cells from the ALLIDB1 dataset using current models. A suggested technique that addresses class imbalance concerns and enhances the accuracy of healthy and blast cell identification and recognition is trained on Improved You Only Look Once Version Four (YOLO v4) inside a Hadoop environment [13].

3. Material Research

3.1 Material Screening

Metal mine dust has small particle size, large viscosity and good dispersion characteristics, and the effect of traditional spray dust suppression technology is limited. Based on the world spray dust suppression technology study, the spray dust suppression materials were screened. Conventional techniques for controlling dust include using water, lignosulfonates, and suppressants based on polymers. Although widespread, water is ineffective in dust or dry environments. Environmentally friendly suppression using biodegradable compounds is now under development. The existing spray dust suppression materials mainly include organic solutions, inorganic salts, polymers, and solutions compounded of inorganic salts and polymers. Among them, inorganic salts and polymer materials have high mechanical strength, are easy to obtain, and are inexpensive. However, they seriously impact the environment and human health and are sensitive to changes in environmental conditions such as temperature and humidity. At present, many new sprays of dust suppression materials have been studied. Still, due to the lack of a unified evaluation standard and system, its dust suppression effect is difficult to evaluate reliably.

Heat transfer, fluid flow, and related processes may all be analyzed using CFD, a numerical simulation method. CFD models may mimic how dust particles behave in the air when impacted by various variables, including airflow patterns, the use of dust suppression materials, and ambient conditions, in the context of dust suppression in metal mines. To select the best material combination, this article combines physical simulation and CFD to conduct a simulation study on the dust suppression effect of the spray. First, the discrete phase model simulates the collision, fusion and sedimentation of dust particles and droplets in the spray process. According to the laws of conservation of mass and momentum, the interaction between particles and fluids is an instantaneous process. Particles move under the influence of gravity, inertia, centrifugal force, and other external forces, which determine particle motion law. Therefore, the particles' interaction must be considered in spray dust simulation. One of the important methods to study the dust suppression effect of spray is by numerical simulation of the dust suppression effect under different combinations of spray dust suppression materials. This article selects three commonly used spray dust suppression materials: polyvinyl chloride (PVC), Poly Vinyl Dene Fluoride (PVDF) and silicone rubber. Due to its strong resistance to weathering and UV radiation, Polyvinyl Chloride (PVC) is an economical and long-lasting material for dust suppression in metal mines. Its chemical resistance makes PVC suitable for outdoor use in severe mining situations. Dust suppression applications in acidic or alkaline conditions benefit greatly from polyvinylidene fluoride's high chemical stability and durability (PVDF). Since water is repelled by its low surface energy, it improves dust binding and is appropriate for hotter climates. Since silicone rubber is elastic, flexible, and water-repellent, it can be used on various surfaces and keeps dust out of the air. It can be used when health-conscious procedures are required because it is non-toxic and ecologically friendly.

PVC has good corrosion resistance, wear resistance, stability, excellent electrical insulation and low thermal conductivity. In addition, PVC is a high-toughness plastic with a fracture elongation of up to 600%. The PVC spray dust suppression material studied in this article consists of a water-based solution, high molecular polymer, silicone surfactant, etc. Its main components are water and silicone surfactant. Water and organic silicon surfactants undergo polymerization reactions in the mixed solution, producing a high polymer - polyvinyl chloride (PVC), which has good fluidity, permeability, corrosion resistance, and excellent electrical insulation properties. Among them, polyvinyl chloride is a thermoplastic elastomer material with good plasticity and toughness. Therefore, it is mixed with other particles to reduce spray dust.

In this article, the dust suppression effect of PVC spray dust suppression material was studied using numerical simulation. PVDF is a new type of polymer material with low density, high strength, corrosion resistance, and ageing characteristics. PVC is simple to work with and sticks to surfaces because of its low viscosity when melted. Because PVDF is low viscosity when melted, it is easy to work with and appropriate for certain uses. The viscosity of silicone rubber ranges from 1.1 to 1.5 g/cm³. However, it can be made with a higher viscosity for certain uses. It has excellent weather resistance, good heat, light, oxygen, and water stability, and no corrosive effect on metals. It is an industrial high molecular material with good comprehensive performance. The advantages of PVDF spray dust suppression materials are mainly reflected in the following three aspects: (1) PVDF spray dust suppression materials mix dust particles with water to form a stable mixture, thus improving its dust suppression effect; (2) The dust suppression principle of PVDF spray dust suppression material is physical adsorption and chemical reaction; (3) PVDF spray dust suppression materials contain a large number of surfactants, forming a hydrophobic film on the surface of dust particles to prevent chemical reaction between dust particles and water. Viscosity, particle size, surface tension, chemical properties like pH, active components like surfactants, polymers, or adhesives, and biodegradability are examples of a dust suppressor's physical characteristics. These elements affect the material's wettability, capacity to spread and stick to dust particles, and ability to satisfy sustainability and regulatory requirements.

Because PVDF sprays dust suppression materials are widely used in industry, this article conducted a simulation study on the dust suppression effect based on this. The discrete phase model simulates the collision, fusion and sedimentation process of dust particles and droplets in the spray process. An essential technique in computational fluid dynamics (CFD) for simulating the behaviour of discrete particles in continuous fluid flow is the Discrete Phase Model (DPM). It combines factors like drag and gravity, helps forecast how particles will interact with spray droplets and help optimize spray settings for the best possible dust suppression effectiveness. The dust reduction effect of spray obtained through physical simulation is good, indicating the model has high accuracy. Comparing the simulation results with the experimental results, it can be found that: (1) There is a certain difference between the particle motion equation used in physical simulation and the actual situation; (2) Under the same spray conditions, PVDF spray dust suppression materials have good dust suppression effects on dust particles with different particle sizes; (3) The particle motion equation used in physical simulation differs significantly from the actual situation, resulting in a certain difference between the dust reduction effect obtained from physical simulation and experimental results.

In industrial applications, silicone rubber is used as an environmental protection material in spray dust suppression. It is a complex mixture composed of various components. The silicone rubber in this article is mainly composed of silicone oxide polymer and vinylidene fluoride monomer. Among them, silicon oxide polymers primarily include polyvinylidene fluoride and their mixtures. Vinylidene fluoride mainly comprises organic substances such as boron trifluoride, sulfur hexafluoride, hydrogen fluoride, and carbon tetrafluoride. In the process of spray, the viscoelasticity of silicone rubber enables it to effectively absorb water, thus achieving the effect of spray dust reduction. In the process of spray, the energy generated by the collision between dust particles and droplets is absorbed by silicone rubber, which greatly reduces the speed of droplets.

3.2 Material Preparation

The performance evaluation of materials includes dust reduction efficiency and stability of use. According to the dust reduction efficiency evaluation index, the commonly used spray dust reduction materials include water, cement, polymer and inorganic compounds. Based on the experimental results, this article studied the performance of three spray dust suppression materials: polymer materials, water and cement. High molecular polymers include Poly Acryla Mide (PAM), Poly Ethylene (PE), polyvinyl chloride (PVC) and Poly Methyl Meth Acrylate (PMMA). Due to their better performance, ability to absorb moisture, high dust binding capacity, adaptability, and affordability, polyacrylamide (PAM) and polyethene (PE) are the materials of choice for dust suppression. Large-scale mining operations may effectively use these materials since they can be used in damp and dry regions. Water is a cheap and easily available spray dust reduction material. Under laboratory conditions, the optimal combination was determined by testing the dust reduction efficiency of three PAM solutions and three aqueous solutions on coal powder within 5 minutes.

Experimental conditions: In air, the mass fraction of PMMA is 10mg/m ^{3}, the mass fraction of PAM is 20%, the concentration of PAM solution is 2%, and the concentration of aqueous solution is 0.5%; The settling time of coal powder in the air shall not be less than 5 minutes, and the mass fraction of coal powder shall not be less than 10%. The dust-reducing material can be moistened with water and mixed evenly. The mixture can be soaked in water for 24 hours before being taken out and naturally dried at room temperature. Three types of water and cement solutions were used for dust reduction experiments. A spray dust suppression device was designed to simulate the settling of pulverized coal in the process of spray dust suppression under actual working conditions. The influence of particle interactions, such as collision modelling, aggregation, and surface impact, on dust suppression performance is assessed by numerical simulations. These methods show how effective the system is under different environmental circumstances. The device includes two parts: a spray system and a wind system. Before the experiment, the inner wall of the device could be polished smoothly and rinsed clean with a high-pressure water gun. Then, the material can be evenly sprayed onto the surface of the coal powder, and finally, the dust reduction effect is tested. PVC is a multipurpose polymer that may be used for plumbing, electrical insulation, building materials, and construction. It also has good mechanical strength and chemical resistance. Silicone rubber is utilized in seals and gaskets, but polyvinylidene fluoride (PVDF) has strong mechanical qualities, is thermally stable, and is chemical resistant. The spray dust suppression device consists of a spray system and a wind system, as shown in Figure 1.

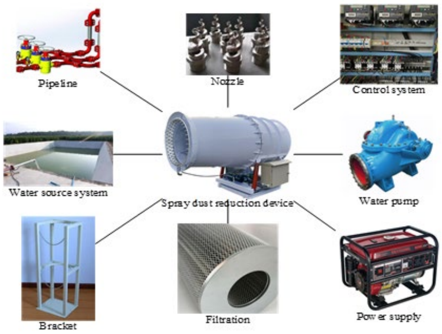

Figure 1. Spray Dust Suppression Device

The spray system comprises a water source system, water pump, nozzle, pipeline, control system, support, filtering system, power supply, etc. When the device is working, the motor drives the belt to rotate, which drives the spray to rotate so that the water in the atomizer is atomized, and many small water drops are generated to condense in the air to reduce dust. The setting of spray parameters mainly considers the dust settling time, particle velocity distribution and particle volume fraction. Particle tracking entails tracking the locations and velocities of particles, whereas velocity field measurement measures the turbulence levels and airflow velocities. Dust cloud motion is captured by high-speed imaging, and statistics are used to compare simulated and experimental data. Due to the inherent viscosity of coal powder, a certain amount of resistance is generated during the settling process, resulting in "ripples" on the surface of coal powder. Industrialization may lower dust emissions in metal mines by utilizing cutting-edge technology such as electrostatic precipitators, misting systems, and HEPA filters. Regular equipment maintenance, automatic water spraying, and reducing disruptions in dust-prone regions all help with dust control. By simulating the trajectory and velocity distribution of droplets, it is found that the velocity of droplets is mainly determined by the droplet radius, and the smaller the droplet radius, the shorter the trajectory. The simulation results show that under the same spray parameters, different material dust suppression devices greatly impact the settling time and particle velocity distribution of pulverized coal under the same spray parameters. The settling effect of pulverized coal is improved by adjusting the spray parameters of dust suppression devices with different materials [14].

The computational fluid dynamics simulation method was used to study the settling velocity of pulverized coal in spray dust suppression, and commercial software was used in Fluent software for numerical simulation. Models frequently make idealized assumptions that might not fully reflect situations that occur in the actual world. Less accurate estimates of dust resuspension can result from particle collisions, limited resolution, imprecise boundary conditions, and real-world unpredictability. The same computational model was used to compare the experimental results, and the numerical simulation results were compared with the experimental results. It is possible to analyze the settling velocity and dust reduction effect of different particle sizes of coal powder under the same conditions and study the influence of coal powder particle size and atomized particle size on its dust reduction effect. To avoid the heterogeneity of the calculation area, a mixed model is used in Fluent to simulate the process of spray dust fall. The model simulates the natural convection in the spray dust fall zone and considers the pulverized coal particles' physical properties and geometric structure in the spray dust fall zone. According to the model, the spray dust fall can be divided into three regions: the gap between the pulverized coal particles, droplets and natural convection. On this basis, coal powder particles with a mass fraction of 1% were defined under boundary conditions. A comparative analysis was conducted using different particle sizes and atomized particles to study the settling velocity and dust reduction effect of varying particle sizes of coal powder. The average settling velocity of coal powder with a particle size of 0.1mm is about 3~4m/s. Under the same conditions, the smaller the particle size of coal powder, the faster its settling velocity; The smaller the atomized particles, the better the dust reduction effect. To simulate the influence of pulverized coal particle size and atomized particle size on the dust suppression effect in the actual spray dust suppression process, three pulverized coal particles with the same size and different diameters were selected in various particle size ranges for comparative analysis. The results indicate that the smaller the atomized particles, the better the dust reduction effect. Since the diameter of pulverized coal particles is less than 0.1mm, it is not easy to settle, so it is necessary to select smaller pulverized coal particles for spray dust suppression.

Dust reduction efficiency refers to the ratio of the mass of dust separated from coal powder to the mass of dust separated from air. The contact area between coal powder and air is large in actual working conditions, resulting in a high dust density. Therefore, under actual working conditions, when the spray area of the spray dust suppression device is greater than the density of pulverized coal, the dust suppression effect can become worse. Calculate the dust reduction efficiency of coal powder under different conditions based on factors such as the initial wetting time of the material surface and the thickness of the material surface after wetting. The calculation method is used to predict the dust reduction effect of the spray. In this calculation, the calculation formula for the settling time of pulverized coal in the air is:

$$t = \frac{D^2}{18v} \quad (1)$$

Among them, D is the diameter of the particle, and v is the kinematic viscosity of the fluid. Spray dust suppression involves covering the face of pulverized coal with a layer of water by spraying dust depressant to increase its contact area with dust so as the dust concentration.

4. CFD Model Construction

During the construction of the CFD model, the following aspects are mainly considered: first, the physical model is established according to the principle of spray dust reduction and the actual operation process; the second is to divide the calculation area into grid cells and determine the calculation boundary conditions through grid partitioning; the third is to establish a mathematical model for computation. Based on the above research, the spray dust reduction process is numerically simulated by the CFD method, and the best scheme is obtained by comparing the dust reduction effect of spray with different materials and different spray speeds. Computationally costly models like CFD are used to estimate the impact of dust suppression. However, this model has several issues, including complexity, data needs, parameter uncertainty, time consumption, and field condition integration. Acquiring high-quality experimental data in dynamic settings such as metal mines is also a challenge. The final model is shown in Figure 2.

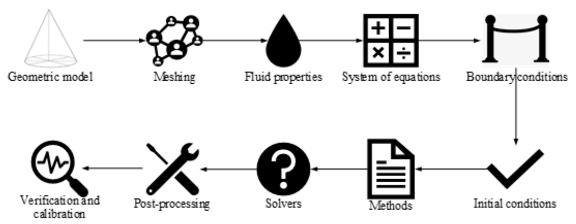

Figure. 2 CFD Model

This is the body text with no indent. The CFD model consists of ten elements: geometric model, mesh division, fluid properties, equation system, boundary conditions, initial conditions, method, solver, post-processing, and validation calibration. A strong, precise, and dependable technique for forecasting turbulent flows is the k-epsilon model, which is especially useful in industrial settings such as mine dust management. It is composed of two transport equations, where ε is the turbulence dissipation rate, and k is the turbulent kinetic energy. In the numerical simulation of the spray dust fall process, the standard k - ε turbulence model, multiphase flow model and standard wall function model are selected to simulate the movement of dust particles in the spray process. In the process of spray dust fall, the particles can fall to the ground under gravity and diffuse with the flow of air. For the convenience of describing particle motion and diffusion, dust particles are considered as two-dimensional translational fluid particles, and their mass conservation, momentum conservation, and energy conservation are assumed.

In order to reduce the computational scale and workload, a discrete phase model is used to simulate particle motion and diffusion processes. The discrete phase model is a computational fluid dynamics method developed from the particle random orbit model [15]. The DPM was selected because of its realistic simulations, focused particle analysis, and compatibility with CFM. It enables researchers to examine the behaviour of dust particles in spray droplets, shedding light on the effectiveness of dust suppression and allowing the investigation of dust dynamics in mining contexts. On this basis, a multiphase flow model based on the finite volume method was introduced to simulate the particle motion and diffusion process. Different turbulence models and grid partitioning methods are used for different computational models. When establishing numerical simulation models, air is treated as a continuous medium and fluid as a discrete phase. Realistic modelling, flexibility, enhanced precision, and economical computing are all provided by multiphase flow simulation for precise tracking of particle trajectories, improving phase interaction representation, and lowering computational complexity. When dust particles come into contact with the air, a series of complex physical processes such as collision, splashing, entrainment, and diffusion occur. In order to avoid direct collisions and entrainment between particles, a coupled solution of the k - ε turbulence model and discrete phase model was adopted.

When establishing the simulation of spray dust fall, the standard wall function method is used to deal with the wall function. The traditional wall function approach and continuous phase have been coupled in spray dust fall scenarios to improve particle motion modelling. This has improved the prediction accuracy of particle behaviour, influenced settling rates and dust buildup, and taken flow patterns and turbulence effects into consideration. In the calculation process, the standard wall function method is used to couple with the continuous phase to obtain the equations of motion for the dispersed phase and particles while considering the interaction between dust particles and gases in contact with air. CFD equations can be established according to the movement equation of dust particles in spray dust suppression. To simplify the calculation process, the calculation area is divided into grid cells when constructing the physical model, and the boundary conditions are determined through grid division. When building the physical model, first determine the simulation conditions of spray dust suppression operation conditions according to the different conditions of the actual operation process. To minimize waste and resource consumption, ensure occupational safety standards, minimize volatile organic compounds, improve system efficiency, monitor airborne contaminants, and recycle materials, industries should investigate environmentally friendly suppression agents such as plant-based or biodegradable polymers. By analyzing the working conditions of spray dust reduction, under the condition of controlling spray speed and material consumption, the spray effects under different spray speeds and material consumption were obtained. The dispersion of dust particles and settling efficiency are influenced by the design of a spray system, which includes the kind of nozzle, droplet size, and spray angle. Dust settling may be influenced by wind systems, and realistic wind modelling is essential to effectively depicting the interaction between dust and spray and real-world situations. Five different materials and different spray speeds were selected for numerical simulation by combining simulation analysis and experimental research to determine the optimal scheme.

When constructing a physical model, the following aspects are mainly considered: first, the movement law of dust particles in the process of spray dust reduction; second, the influence of airflow on dust particles; third, the influence of different materials on the effect of spray dust reduction; fourth, the influence of different materials and different spray speeds on the operation effect. When constructing a physical model, the following aspects are mainly considered: first, the movement law of dust particles; second, the physical process of dust particles in contact with air; third, the diffusion process of dust particles after contact with air; fourth, the pressure distribution of dust particles after contact with air. In the process of spray dust reduction, the movement speed of dust particles is relatively fast, so when establishing the model, the calculation area should be reasonably meshed to ensure the accuracy of the calculation results. For the initial direction of the dust particles during the spray dust reduction process, the horizontal orthogonal rotating coordinate system under the rotating coordinate system is used, and the final direction of the dust particles is perpendicular to the direction of movement through the iterative solution. During the simulation process, the initial direction of the dust particles is adjusted by changing the parameters of the spray inlet, spray speed, and spray distance [16].

In the process of spray dust reduction, dust particles can produce many initial velocities, so the initial velocities of dust particles are adjusted by changing the parameters of the spray inlet. In the spray inlet parameters, spray pressure and spray flow are taken as independent variables; spray pressure is set to 10MPa, and spray flow is set to 30L/min. One variable is set as the initial condition in the model; when the nozzle is opened, the change value of spray pressure is 0, and when the nozzle is closed, the change value of spray pressure is 10 MPa. The range of values for this variable can be determined through experimental data. During the simulation, the experimental data is calibrated according to different conditions to determine the range of values for other variables in the simulation model. In practical applications, parameters such as nozzle opening pressure and flow rate are adjusted according to different dust concentrations to regulate the initial velocity of dust particles. The selection of spray speed and distance is very important when simulating the process of spray dust fall. By adjusting the spray speed and distance, the trajectory of dust particles in the spray area is smoother, thus reducing the retention time of dust on the particle surface. Therefore, the spray speed and spray distance should be reasonably controlled to ensure the accuracy of the simulation results. The above analysis shows that the spray speed and distance are reasonably set. In numerical simulation, the atomization effect can be simulated by adjusting the relative motion between two different forms of droplets and dust particles. According to the fluid dynamics theory, the relative motion between atomized droplets and dust particles is a completely nonlinear system of partial differential equations [17-18].

$$\frac{u}{t} + u\frac{u}{x} + v\frac{u}{y} = -\frac{1}{\rho}\frac{P}{x} + v(\frac{u}{x^2} + \frac{u}{y^2}) \ (2)$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \ (3)$$

Among them, u is the velocity component, P is the pressure, ρ is the density, and x and y represent the direction. Due to the fast movement speed of dust particles in the airflow, the inertia of dust particles is not considered in the calculation process to reduce computational complexity. The Lagrangian interpolation method can be applied to obtain the motion trajectory of dust particles in a rotating coordinate system. The steps involved in simulating dust particle movement are as follows: locate important locations in the flow field, interpolate using known velocity data points, estimate beginning velocity at unmeasured places using Lagrange interpolation, and utilize the computed values as the initial conditions for particle movement. Therefore, the Lagrange interpolation method is used in the calculation process to determine the initial motion direction of dust particles. Due to the iterative solving process, the solution area is divided into multiple small blocks. According to the calculation results, the Euler Euler model can be applied in each small area. The movement trajectory of dust particles in the previous small area can be used as the initial direction of movement in the next small area. Using grid partitioning techniques, the calculation area is divided into finite element grids or meshless elements. Then, the calculation area is meshed based on the motion parameters, initial velocity, motion trajectory, and motion direction of dust particles in the finite element grids or meshless elements. Different initial conditions are set to simulate the process of dust particles contacting the air, and the movement of dust particles in the process of spray dust suppression under different parameters is simulated. When the finite element method is used to simulate the spray dust fall process, the calculation area is divided into two types: fixed volume element and random volume element. When the finite element method is used to simulate the process of spray dust suppression, it needs to be realized by programming the calculation software. In the finite element simulation, the numerical calculation method and boundary conditions are used to determine the boundary conditions in spray dust suppression [19].

5. Test experiment of New Spray Dust Suppression Material

At present, spray dust suppression technology has been widely used. According to the actual situation of the scene, this article studies a new control method of spray dust suppression and uses this method to test the scene. First, the effect of spray dust reduction is controlled by controlling the spray rate of the nozzle. Secondly, the intensity of spray dust reduction is controlled by adjusting the fan air volume and air pressure. Finally, the effect of spray dust reduction is tested by monitoring the dust concentration on the site. When dust exists in the air, it can collide, merge, disperse, and settle with water. The best combination of spray dust suppression is determined by analyzing this process, as shown in Table 1.

Table 1 Dust Prevention Experiment Results

Material Concentration (%)	Dust Suppression Rate (%)	Temperature (°C)	Humidity (%)
0.5	95.5	22	40
1	92.3	23	45
1.5	89	21	42
2	80.9	24	50
2.5	86.9	20	38
3	75	22	41
3.5	70.5	23	44

In Table 1, when the material concentration is 0.5%, the dust reduction rate reaches as high as 95.5%; When the material concentration is 1%, the dust reduction rate is 92.3%; When the material concentration is 2%, the dust reduction rate is 80.9%; When the material concentration is 2.5%, the dust reduction rate is 86.9%. This research has developed a new type of spray dust reduction material. The chemical dust reduction method is used to simulate the sedimentation of pulverized coal in the spray process, and compared with the actual working conditions, the dust reduction effect and use stability are analyzed. The results are shown in Figure 3 and Figure 4.

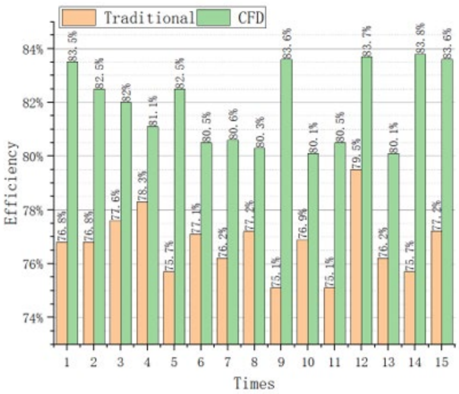

Figure 3. Dust reduction efficiency

In Figure 3, traditional dust-reducing materials' highest dust-reduction efficiency is 79.5%, the lowest is 75.1%, and the calculated average efficiency is 76.76%. Compared with conventional materials, the dust reduction efficiency of the new spray dust reduction material developed by CFD has improved significantly, with the highest efficiency of 83.8%, the lowest efficiency of 80.1%, and the calculated average efficiency of 81.89%. The new spray dust suppression material based on CFD has higher dust suppression efficiency.

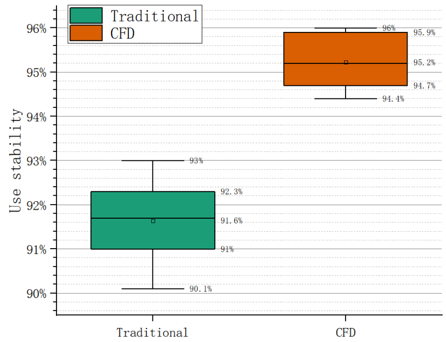

Figure 4. Stability of Use

In Figure 4, the stability of traditional dust-reducing materials is highest at 93%, lowest at 90.1%, and the calculated average stability is 91.6%. Compared with conventional materials, the use stability of the new spray dust suppression material developed by CFD has improved a lot, with the highest stability of 96%, the lowest of 94.4%, and the calculated average stability of 95.2%. The new spray dust suppression material based on CFD has higher stability. In addition, this article also made statistics on the types of spray particle size, as shown in Table 2.

Table 2 Spray particle Size

Spray type	Droplet size range (μm)	Spray velocity (m/s)	Diffusion angle (°)
A	5-10	20	30
B	10-15	15	25
C	15-20	18	35
D	20-25	25	40
E	25-30	22	45

Table 2 shows that the particle size range of each spray type is different. The particle diameter of type A is between 5 and 10 microns, while type E's is between 25 and 30 microns. The spray speed has a significant impact on the coverage. The spray speed of type D is 25 meters per second, the fastest of the five types. The diffusion angles also vary, with Type E having a diffusion angle of 45 degrees, covering a larger area and effectively capturing more dust. The specific research results on coverage are shown in Figure 5.

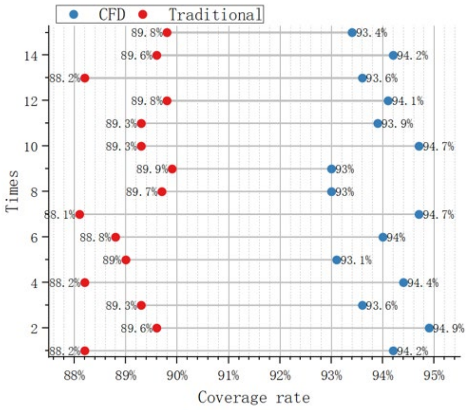

Figure 5. spray Coverage

In Figure 5, the highest coverage rate of traditional spray dust suppression materials is 89.9%, the lowest is 88.1%, and the calculated average coverage rate is 89.12%. Compared with conventional materials, CFD's new spray dust suppression material has a much higher spray coverage rate, with the highest stability of 94.9%, the lowest of 93%, and the calculated average coverage rate of 93.92%. The new spray dust suppression material based on CFD has higher spray coverage. At the same time, this article also conducted statistical analysis on dust concentration, as shown in Table 3.

Table 3 Dust concentration

Test point	Dust concentration (mg/m³)	Measurement time (s)	Humidity (%)
Point 1	150	60	40
Point 2	200	60	45
Point 3	100	60	30
Point 4	250	60	50
Point 5	180	60	35

In Table 3, the dust concentration shows the degree of pollution in different environments, with the highest point reaching 250 mg/m ³ at point 4, indicating that the dust problem in this area is relatively serious. The test time is 60 seconds to ensure the consistency of the data, and the humidity change may also affect the spray effect. The humidity in Point 2 is 45%, while that in Point 3 is lower, only 30%. These data, combined with spray characteristics, provide a basis for evaluating the effect of spray dust suppression materials, and further analysis helps develop and apply new dust suppression materials. Finally, this article conducted a satisfaction survey on five spray dust suppression materials, and the results are shown in Table 4.

Table. 4 Satisfaction Survey

Dust removal materials	Very satisfied	Satisfied	General	Dissatisfied	Very dissatisfied
PVC	15%	21%	47%	8%	9%
PVDF	22%	20%	45%	6%	7%
PAM	17%	24%	50%	9%	0%
PE	15%	25%	49%	10%	1%
PMMA	20%	23%	48%	5%	4%

In Table 4, based on user satisfaction surveys with different dust-reducing materials, the performance of PVC, PVDF, PAM, PE, and PMMA varies. The satisfaction rate of PVC is relatively average, with 15% of users expressing very satisfied, 21% satisfied, 47% considering the effect to be average, and 8% and 9% of users expressing dissatisfaction and dissatisfaction, respectively, indicating room for improvement. The feedback on PVDF is relatively good, with 22% of users being very satisfied, 20% satisfied, 45% considering the effect average, and only 6% and 7% of users expressing dissatisfaction or dissatisfaction. Overall, PVDF and PMMA have achieved high user satisfaction, while PVC and PE need further optimization and improvement to enhance their dust reduction effect.

6. Conclusions

In this article, the spray dust suppression technology of metal mine dust is deeply studied, the limitations of traditional dust suppression materials are analyzed, and the application effect of new spray dust suppression materials is explored. By means of numerical simulation and experiment, the dust suppression efficiency, application stability and spray characteristics of different materials were evaluated in detail. The research results show that the new polymer materials have excellent dust suppression effects and user satisfaction, significantly better than the traditional spray dust suppression materials. In the process of spray dust suppression, the interaction between droplets and dust particles, the physical properties of materials and environmental conditions have an important impact on the dust suppression effect. Through the optimization design of the spray system and the reasonable setting of spray parameters, the coverage and efficiency of spray dust reduction can be effectively improved. At the same time, the spray effect under different dust concentrations and humidity conditions was systematically analyzed, providing a scientific basis for practical application. In addition, the satisfaction survey results show that the differences in user experience among different dust-reducing materials offer direction for improving and developing subsequent materials. Future research should further explore the development and application of new environmentally friendly materials, combined with modern technological means, to enhance the effectiveness of dust reduction technology to address the increasingly severe problem of dust pollution.

Declarations

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Code availability: Not applicable.

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