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Review

Review on Dust Control Technologies in Coal Mines of China

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Abstract: China faces a challenge in the sustainable development of the coal industry due to pneumoconiosis problems. Dust control technologies are crucial for safe production and miners' health, ensuring the industry's longevity. This article reviews the development process of dust prevention and control in underground coal mines in China, summarizes various technologies, and divides them into dust suppression, open-space dust reduction, and mine dust collectors according to different stages and environments of use. In dust suppression technologies, coal-seam water injection can reduce total dust generation by 60%, wet rock drilling can reduce drilling dust in the presence of stable water sources and high-pressure bearing equipment, and water-seal blasting can reduce blasting dust by 50–70%. In open-space dust reduction technologies, spray dust suppression can remove total dust by 50–95% and the removal efficiencies of foam dedusting for total and respirable dust are reported to reach 95% and 85% under the right conditions, respectively. In dust collector technologies, dry collectors can remove 80–95% of total dust. Wet collectors achieve up to 90% efficiency, dependent on water supply and waste processing. This article also discusses vapor heterogeneous condensation technology as a promising method for improving respirable dust removal in humid mine environments.

Keywords: coal mine; dust control; dust suppression; open-space dust reduction; mine dust collector; sustainable coal industry

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1. Introduction

Coal is a major energy source and a valuable strategic resource. However, with the improvement in mechanized mining capacity, the problem of dust underground in coal mines is becoming increasingly serious. Mine dust consists of coal dust, rock dust, and other toxic and harmful dust produced during underground operations [1]. Mine dust is primarily generated by underground activities, such as drilling, blasting, cutting, coal dropping, loading, transporting, lifting, and shotcrete construction [2]. The amount of dust production depends on the type and mechanized level of the working face. Generally, higher mechanized workplaces tend to generate more mine dust [3]. The dust generation also differs among working faces due to different production processes and operation methods [4]. Figure 1 shows that the coal mining surface is the primary dust source in coal mines, contributing to about 60% of the total dust [5]. This dust mainly originates from the transport and cutting of coal by mining machines. The tunneling surface is the secondary dust source, accounting for about 30%. Dust is generated during tunneling when the shearer cutting head crushes coal and rocks, and the falling coal collides with the ground and equipment [6]. The anchor spraying surface produces about 7% of the dust, while other operating surfaces contribute 3%.

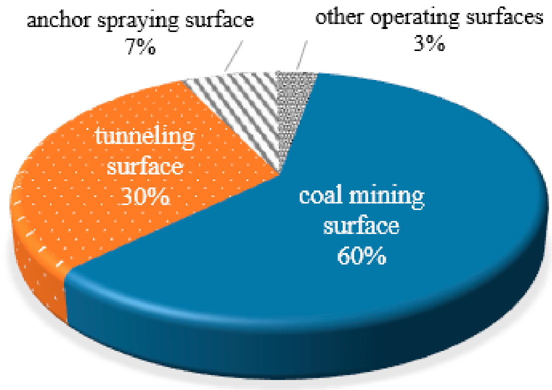

Figure 1. Dust production from different working faces in coal mines.

Mine dust can cause an explosion under certain particle size and concentration conditions [7]. It can also lead to chronic poisoning due to sulfide mine dust and mineral dust containing toxic elements such as arsenic, lead, mercury, and chromium [8]. Moreover, mine dust can cause pneumoconiosis, the most severe occupational disease threatening workers' health. Pneumoconiosis is a general term for pulmonary fibrosis caused by long-term inhalation of a large amount of suspended dust, mainly respirable dust (aerodynamic diameter is below 7.07 μm, with the collection efficiency of dust with an aerodynamic diameter of 5 μm being 50%), which occurs commonly among coal miners [9]. According to the National Health Commission [10], China has reported an annual average of 28,000 new cases of occupational diseases since 2011, of which pneumoconiosis accounted for about 86.3% (Figure 2). By the end of 2022, the cumulative total of reported occupational diseases was 1,037,000, of which pneumoconiosis accounted for about 90% (922,500 cases) [11]. Furthermore, coal mine pneumoconiosis accounted for nearly half of the reported cases of occupational pneumoconiosis. Therefore, mine dust poses a serious threat to the safety and health of underground workers.

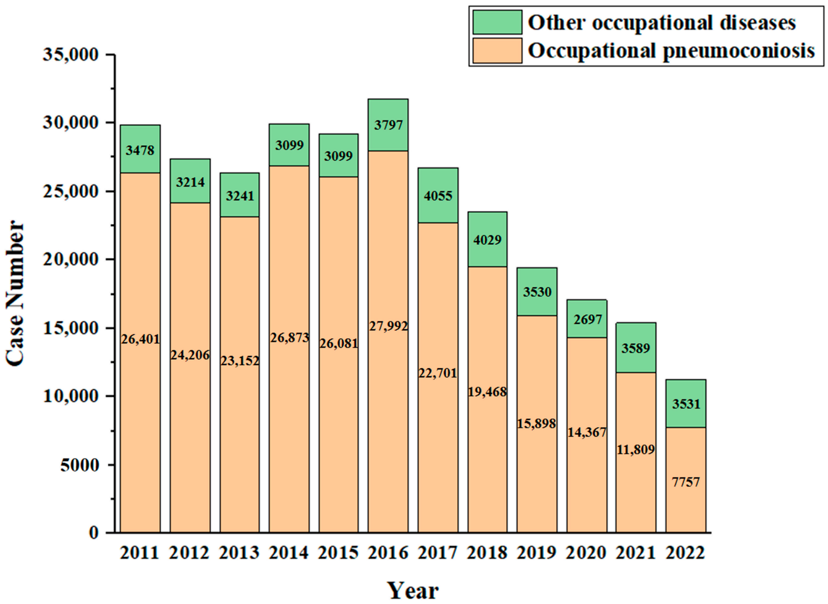

Figure 2. New cases of occupational diseases in the country, 2011–2022 [12].

The health and safety of operators are treasured and prioritized in China, with various measures being implemented to reduce the harm of coal mine dust, thus decreasing the incidence rate of pneumoconiosis. The measures include providing protection education and training for workers, enhancing the health management system, and developing advanced dust prevention technologies and equipment for coal mines [13]. These efforts have yielded positive outcomes, in which dust control technologies make a crucial contribution.

Regarding underground dust prevention technology in coal mines, ventilation can provide fresh air and remove dust from the mining environment [14], a fundamental method for controlling dust [15]. Its effectiveness is unstable, depending on various factors, such as the location and intensity of dust sources, tunnel structures, dust properties, and environmental conditions [16]. Therefore, ventilation alone may not be adequate to reduce dust to an acceptable level, especially when the dust production rate is high. In such cases, some specialized dust control technologies are usually needed to achieve satisfactory results.

In the 1940s, China gradually began to adopt wet rock drilling mining schemes underground to reduce dust concentration during the mining process. In 1956, China first used coal-seam water injection in the Caitun coal mine in Benxi and achieved good results [17]. Starting in the 1960s, Chinese researchers extensively studied and referred to the underground dust prevention and control technologies of countries such as Germany and Poland, and they began studying various chemical dust suppressants and surfactants. They also introduced mining dust collectors from abroad. In the 1980s, surfactants were widely used in underground dust removal. In addition, researchers began to optimize the application schemes of various technologies. The shearer's internal and external spray technology and the spray technology between hydraulic supports achieved automatic control [18]. High-efficiency dust prevention schemes such as coal-seam water injection combined with internal and external spray gradually began to be applied. As of 1990, 40% of coal mining faces in China had adopted coal-seam water injection technology, and China had also developed mining dust collectors. Coal-seam water injection, spray dust reduction, foam dust removal, mining dust remover, and other technologies now have relatively mature application systems [19]. Since then, underground dust prevention technology for coal mines has continuously developed in automation and intelligence, ensuring efficient operation while possessing higher safety and environmental performance.

The application scenarios of dust prevention and control technology in coal mines can be divided into three stages: dust generation, dust transmission, and local dust reduction. Based on this, we divide dust prevention and control technologies into dust suppression, open-space dust reduction, and mine dust collectors. Dust suppression corresponds to the stage of dust generation, and can effectively suppress dust generation and reduce dust from the source. Open-space dust reduction corresponds to the dust propagation stage, and this technology can efficiently remove dust during the propagation process in open spaces. Mine dust collectors correspond to the inhalation stage, which can efficiently and accurately reduce dust in local spaces to avoid harm to human health or other accidents caused by dust.

This article provides detailed introduction about the principles, research, and application status of each type of technology and analyzes the advantages and limitations of each technology as a whole. Finally, the future development direction of dust prevention and control technology in underground coal mines in China will be proposed. This work aims to assist new workers and practitioners in quickly grasping the advancements of coal mine dust prevention and control technologies in China and provide new ideas and insights for their future development.

2. Dust Suppression Technologies

Dust suppression technology is a method that prevents and controls dust by reducing the amount of dust generated at the source, which is a proactive way of tackling the dust problem. It can fundamentally reduce dust, but it is greatly affected by the environment and process level during use. The general dust removal efficiency range is 15–70%. Some common dust suppression technologies include water injection into coal seams, wet rock drilling, and water-seal blasting.

2.1. Coal-Seam Water Injection Technology

Coal-seam water injection is a method of pre-wetting the coal body by injecting water into coal seams before mining to reduce dust production during the mining process [20]. It is one of the most basic and effective dust control measures for coal mining, as it reduces the dust generation at the source. Studies report that coal-seam water injection can reduce dust generation by about 60% during coal mining [21]. Due to its lower cost and good dust suppression effect, it has been widely used in coal mines [22].

Figure 3 shows the water injection into a coal seam to wet the coal body. This process can be roughly divided into three stages: the water inlet stage, the water storage stage, and the water adsorption stage [23]. In the water inlet stage, pressurized water enters the coal body through cracks between coal seams. In the water storage stage, the water injection pressure increases, causing the fissure system in the coal body to develop and expand gradually, creating more channels for water to flow and accumulate in pore fissures. In the water adsorption stage, the water seeps along the channels and is slowly adsorbed by various fine pores and fissures of the coal body. These processes result in a fully wetted coal body [24].

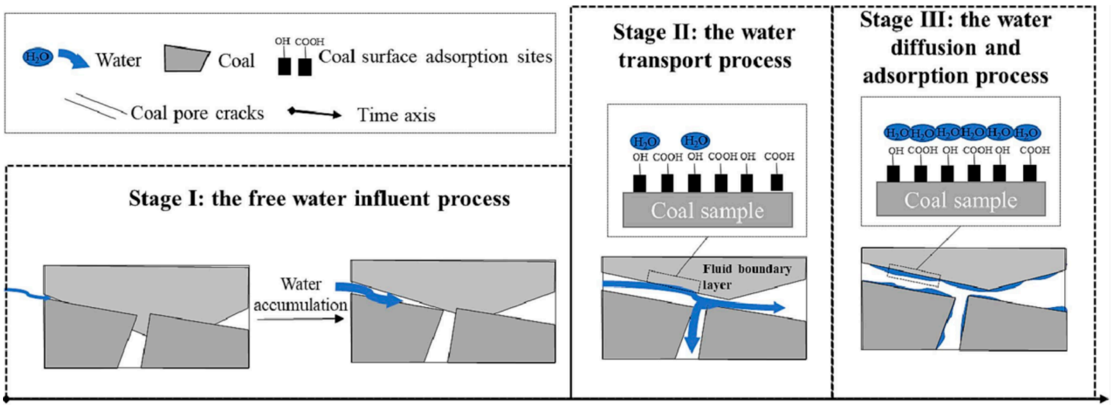

Figure 3. Water injection into the coal seam to wet the coal body. Reproduced with permission from Yang, M., etc., journal "*Fuel*"; published by Elsevier, 2023 [23].

Qin et al. [25] proposed the regression equation of the water absorption and water loss rate as a function of the pore dimension number and maximum pore diameter in 2000, theoretically confirming the feasibility of water injection to wet the coal body. They also found that the effectiveness of water wetting coal is closely related to dust reduction efficiency. Their research provides a basis for optimization of coal-seam water injection.

Researchers found that changing the properties of water can improve the wetting effect of water on coal. Nie [26] and Li [27] studied the microscopic mechanism of water adsorption by coal and showed that magnetized water and surfactants could improve water wetting coal bodies [28]. Cheng et al. [29] added 0.1% sodium dodecyl benzene sulfonate (SDBS) to water and found that it can reduce the surface tension of water and enhance the effectiveness of coal-seam water injection. Xu et al. [30] analyzed the mechanism of sodium dodecylbenzene sulfonate and sodium dodecyl sulfate (SDS) enhancing coal wetting from a microscopic perspective and discussed their applicable environments. Sun [31] utilized efficient wetting enhancers, Wang [32] employed viscoelastic surfactant (VES) fracturing fluid, and Wang [33] used bisamide-based cationic surfactants; their findings demonstrated that the application of these three reagents effectively enhanced the wetting effect of water on coal. The above research indicates that using surfactants or magnetized water can enhance the wetting effect of water on coal seams, increasing the final dust suppression efficiency of coal-seam water injection.

The effect of water wetting coal bodies also depends on the water injection process. Some researchers hope to improve the wettability of coal by optimizing the water injection process. Wang [34] simulated the water injection and seepage process in the coal seam and obtained the effects of confining pressure and water injection pressure on the permeability of coal bodies. Through simulation research, Bai et al. [35] found that higher fracturing fluid viscosity and injection pressure can effectively increase the interlayer penetration ability of hydraulic fractures. Lower fracturing fluid viscosity helps hydraulic fractures extend along horizontal bedding planes. Cheng et al. [36] proposed a scheme of continuously adjusting the injection pressure with the progress of injection time for low-permeability-pressure coal beds in 2012, effectively improving the water injection to low-permeability-pressure coal beds. Wei et al. [37] and Wang et al. [38] showed that adding surfactants to fracturing fluid can significantly improve the water injection in coal seams. In addition, Wang [39] proposed to use gaseous CO_2 pressurization and liquid CO_2 injection for cold leaching of coal, which increased the water adsorption in coal by 3.6 times. In summary, measures such as adjusting the injection pressure and fracturing fluid viscosity appropriately during the water injection process, adding surfactants to fracturing fluid, and carbon dioxide cold leaching of coal can also effectively improve the effectiveness of coal-seam water injection.

2.2. Wet Rock Drilling Technology

Wet rock drilling is a method of continuously supplying water to the borehole during rock drilling. The water moistens and binds the dust to form a slurry discharged from the borehole wall, effectively reducing the dust emission during drilling operations [40].

To improve the performance of wet rock drilling in reducing fine dust, researchers have attempted to modify the properties of the liquid. Lin [41] explained the principles of improving dust suppression with wetting agents, magnetized water, and high-pressure water based on micro-mechanisms. Zhou [42] applied foam to wet rock drilling and experimentally verified its improved dust suppression effect. Anderson [43], Sharma [44], and Cuiec [45] tested the effects of various drilling fluids on the wettability and permeability of rock formations. The above research shows that the dust suppression efficiency of wet drilling can be improved to some extent by changing the physical and chemical properties of the liquid, such as by magnetization, or adding surfactants and using foam and other substances.

Optimizing fluid supply strategies can also enhance dust reduction during rock drilling. Some researchers have found that the drilling fluid injection rate [40], drilling fluid components [46], and water injection pressure [47] affect the dust control performance. Furthermore, Jiang et al. [48] reported that the internal and external water jets on coal mining machines can reduce dust concentration by 90% and 65%, respectively. Liu et al. [49] adjusted the water supply pressure and improved the sealing structure, which can increase the drilling speed by 20–25% while ensuring the dust reduction effect. Hou [50] achieved a 94% dust removal efficiency using a trolley-type water tank pressurized spraying technology for wet rock drilling.

2.3. Water-Seal Blasting Technology

Water-seal blasting, also known as cement blasting, is a technique that injects pressurized water into a borehole filled with explosives and sealed with a hole sealer before blasting [51]. The pressurized water turns into water vapor and microscopic water droplets suspended in the air under high temperature and pressure caused by blasting, which can adsorb gas and capture dust to reduce their concentrations [52].

Studies have been conducted to improve the performance of water seals regarding the inhibitory effect on dust generation and diffusion during the blasting process. Cui [53], Sun [54], and Zou [55] simulated the blasting process and obtained the generation and diffusion laws of blasting dust. Liu [56] established the quantitative relationship between the quantity of explosives, the water-seal height, and the dust production to optimize blasting parameters. Liu et al. [57] proposed an optimal charging structure based on stress, vibration speed change, and dynamic damage. Huang et al. [58] studied the mechanism of borehole blasting in aqueous media and optimized the charging structure to reduce dust production and save blasting costs. These studies optimized the water-seal blasting process in terms of charge quantity, charge structure, and water-seal height, giving it better dust suppression effects and providing valuable theoretical guidance for implementing and applying water-seal blasting.

Practical studies have demonstrated sound dust suppression effects of water-seal blasting. Zhao [59] applied water-seal blasting technology in the 4305 working faces of Hengda Company and achieved a 70% reduction in dust concentration. Zan et al. [60] used water-seal blasting technology in the flat mining project of a phosphorus mine in Guizhou and reduced the blasting dust by 51.5%. Cao [61] filled gun holes with water bags in 2020 at the Harsusu open-pit coal mine and obtained over 75% dust reduction in the blasting area. In summary, under the guidance of extensive theoretical research, the current water-seal blasting technology can achieve a total dust suppression efficiency of 50–70%.

3. Open-Space Dust Reduction Technologies

Open-space dust reduction is a method of removing dust in a space where air flows freely. It performs dust reduction during the process of dust diffusion. This section mainly introduces two techniques: spray dust reduction and foam dust removal.

3.1. Spray Dust Reduction Technology

Spray dust reduction technology is a technique that sprays water or other dust removal solutions into the air through nozzles, and its dust reduction efficiency for the total dust can generally reach 50–95% in various environments. The sprayed solution droplets contact and collide with dust particles in the air (Figure 4), increasing their size and weight. As a result, the dust in contact with the droplets settles to the ground under the influence of gravity, thereby reducing the dust concentration in the air [62]. Spray dust reduction is widely used in underground environments. It has the advantages of low cost, simplicity, environmental adaptability, and high efficiency [63].

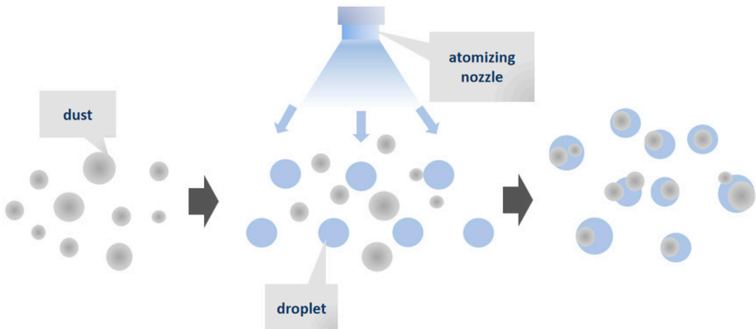

Figure 4. Process of dust contact with droplets.

The efficiency of dust reduction through spray is influenced by atomization, which is related to the spray pressure, the relative speed of dust and droplets, and nozzle diameter [64]. Cheng et al. [65,66] reported that higher spray pressure leads to smaller droplet sizes, resulting in better atomization and dust reduction. They found that increasing the spray pressure from 2.0 MPa to 8.0 MPa could enhance the overall dust reduction efficiency from 92.7% to 98.5%. Jing et al. [67] studied the collision between dust and droplets and observed that a higher relative velocity resulted in higher inertial force, leading to better dust removal. Wang et al. [68] examined the dust reduction effect of atomizing nozzles with different outlet diameters. They reported that the dust reduction efficiency increased by 7.32% when the nozzle diameter increased from 2 mm to 4 mm. In conclusion, selecting appropriate nozzles and optimizing spray pressure can increase the dust reduction efficiency of spray by 5–10%.

The solution characteristics are also crucial for spray dust reduction. Pure water is predominantly used but has some limitations, such as high pressure on the nozzle system and poor removal of respirable dust [69]. Researchers have attempted to modify the solution by adding wetting agents and active agents or magnetizing the spray water to enhance the wettability of the droplets and improve the removal of small particles [70,71]. Zhou [72] studied the trapping effect of surfactant-magnetized water on coal dust. Figure 5 shows how the surfactant solution is magnetized to form a denser surface adsorption layer, improving the solution droplets' wettability. Their research shows that the dust reduction efficiency of surfactant-magnetized water is 8.21% higher than that of surfactant without magnetization. Cheng et al. [73] tested four surfactant solutions: sodium sec-alkyl sulfonate (SAS), 1631 cationic surfactant, cocoamidopropyl betaine (CAB-35), and JFCS nonionic surfactant, and found that they could all substantially improve the respirable dust reduction efficiency to more than 90%. Li et al. [74] showed that surfactant-enhanced water spraying could increase dust removal by 40% compared to pure water spraying. Chen et al. [75] demonstrated that magnetized water had better wettability and dust removal efficiency than non-magnetized water, and its dust reduction rate could be 16.36% higher than that of non-magnetized water under optimal conditions. Furthermore, the use of dust suppressants containing alkylphenol ethoxylate (APEO) [76], sodium dodecylbenzene sulfonate and sodium polyacrylate [77], polyacrylamide [78], and Gemini surfactant [79] have been proved to effectively improve the performance of spray dust reduction. Compared with optimizing spray parameters, adding various surfactants or magnetized water can significantly improve the efficiency of spray dust reduction, which generally increases by 10–40%.

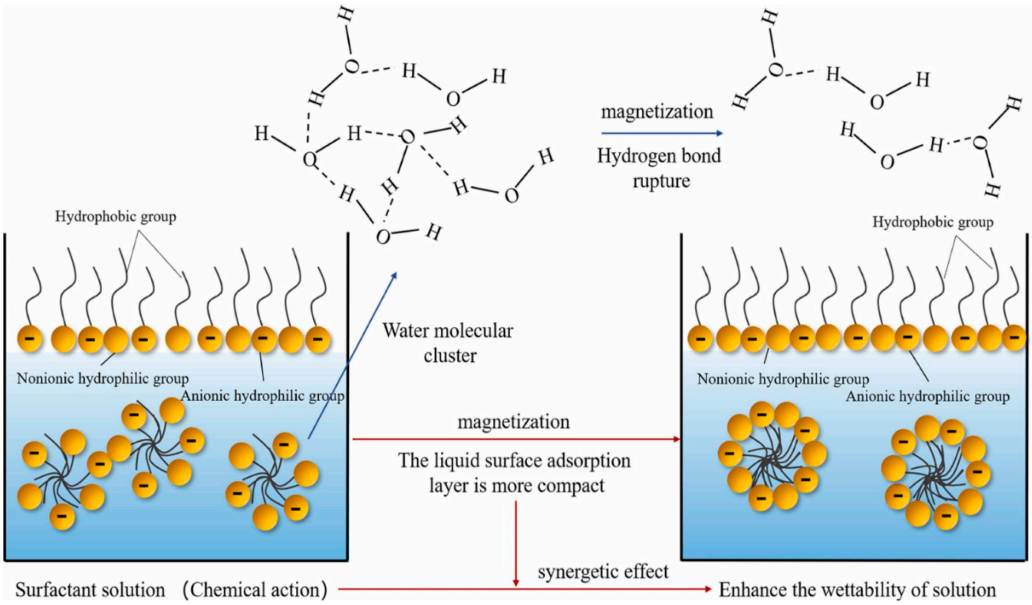

Figure 5. Surfactants improve solution droplet wettability. Reproduced with permission from Zhang, Q., etc., journal "*Process Safety and Environmental Protection*"; published by Elsevier, 2022 [71].

Spray dust reduction technology has performed well in underground dust removal applications. Researchers have designed various devices and methods to improve its effectiveness and adaptability. Tang et al. [80] designed an external spray dust suppression device for a continuous miner, which could conveniently adjust the atomizing nozzle's spray direction. The device reduced the total dust by 82.3%. Guo et al. [81] applied three-dimensional covering sprays to the dust source in the Hongliulin Coal Mine and achieved a dust removal efficiency of 89.76% for the respirable dust downwind of the shearer. Wang et al. [82] added surfactants to reduce the tension of water to achieve better atomization, which improved the respirable dust reduction rate to 85%. Hou et al. [83] designed and applied a self-powered dust removal system for long-distance conveying belts in underground coal mines, which reduced respirable dust in the transport roadway from 6.33 mg/m^3 to 2.48 mg/m^3.

3.2. Foam Dust Removal Technology

Foam dust removal is a technique that mixes water and foaming agents in a specific proportion, generating and spraying a large amount of foam on the dust source or in the dusty air to diminish suspended dust. When the foam is sprayed onto the dust-producing source, the foam body covers and isolates the dust source to prevent dust generation [84]. When the foam is sprayed into the dusty air, it forms many foam clusters with a large volume and surface area to contact with and capture dust [85]. Foam dust removal technology can complement spray dust reduction or serve as a standalone dust removal method in the fully mechanized mining face. It consumes less water than spray dust reduction technology but performs better dust removal [86].

Jiang [87] and Huang [88] reported that the foam dust removal in the air mainly relied on the contact between foam clusters and dust particles, which was mainly affected by the foam properties. They also found that enhancing the wetting and adhesion ability of the foam to the dust can improve dust capture efficiency. Jiang [89] studied the foaming process and found that the composition of the foaming agent is the main factor affecting the dust capture performance of the final foam. Some experiments were conducted to optimize the composition of foaming agents. Duan et al. [90] measured the foaming amount and foam half-life (the time for the foam height to drop by half after foaming) of sodium dodecyl sulfate (SDS) solution and sodium dodecyl benzene sulfonate (SDBS) solution using the improved Ross Miles method. They reported that the optimal mass fraction of foaming agents was 2% under the experimental condition. Xu [91] used molecular dynamics simulation to calculate the foaming performance of polymer stabilizer composite foaming agent in an underground environment and found that adding polyhydroxy polymer stabilizer can improve the foaming performance of surfactant solution. He developed a foaming agent with good performance at low concentrations, achieving a dust removal rate of 89.9% when the foaming agent concentration was 0.1%. Wang [92] found that the polymer can significantly increase the surface viscosity of the foaming agent solution and slow down the foaming rate, which improves the foam stability. These studies provide references for the selection and optimization of foaming agents.

The foam dust removal technology has been applied to underground mines and achieved good performance. Ren [18] used the foam dust reduction technology in Xin'an Coal Mine in 2009 and significantly improved the total dust removal compared with water mist. Huang et al. [93] tested a foam spray dust remover in the Yangquan Mine in Shanxi Province, China, and achieved removal efficiencies of more than 95% and 85% for total and respirable dust, respectively. Han et al. [94] proposed a high-efficiency foam jet device with an arc fan to improve the contact between dust and bubbles, which improved the dust removal efficiency to 92.5%. In 2014, Jiang [95] formulated a foam dust suppressant, which achieved average total and respirable dust reduction of 87.8% and 80.7%, respectively. Wang [96] designed an integrated foam–water mist dust removal device that could reduce 95% of total dust. These examples show that the dedusting efficiency of foam dust removal technology for total and respirable dust can reach nearly 95% and 85%, respectively, under appropriate conditions.

4. Mine Dust Collector Technology

A mine dust collector draws dusty air into the device and captures the dust particles, thus purifying the airflow [97]. Mining dust collectors can be divided into two types: dry and wet.

4.1. Dry Dust Collectors for Mines

Dry mine dust collectors can be further classified into two categories: with or without filter media.

The commonly used underground unfiltered dust collectors include dry inertial collectors and dry cyclone collectors, with a dust removal efficiency for total dust generally around 80–95%. An inertial dust collector uses the inertia of dust particles to make them collide with a baffle and be captured. The dust removal efficiency usually increases with the airflow velocity [98]. Nie et al. [99] simulated the internal flow field of an inertial dust collector using Fluent to determine its optimal inlet air velocity. Yang [100] modified the ducts of an inertial dust collector in the Supplementary Lianta Coalmine to substantially improve the dust removal efficiency. A cyclone dust collector is a device that separates dust particles from dusty airflow by centrifugal force and traps them on the device wall. The separated dust particles then fall and are collected due to gravity [101]. Kanojiya [102] designed a single-stage cyclone dust collector and found its total dust removal efficiency to be more than 90%. Xing et al. [103] analyzed the relationship between the dust removal efficiency and the height of the cylinder, the resistance, and the inlet air velocity through numerical simulation. They found that the dust removal efficiency for total dust can reach 80.22% under optimal operating parameters.

Dry mine dust collectors with filter media are also called dry filtration dust collectors, which use fiber fabric as filter media to filter out the dust in the airflow [104]. Their removal efficiencies of 1~2 μm dust can reach 98~99% under suitable conditions, which are mainly affected by the internal structure and the type of filter media [105]. Researchers have designed and applied various dry filtration dust collectors using different filter materials and structures. Zhou et al. [106] developed the KCG-200D dry filtration dust collector using high-precision filter materials and a pleated cartridge structure. This collector was implemented in Gequan Coalmine, obtaining removal efficiencies of 97.39% for total dust and 96.41% for respirable dust. Li et al. [107] designed a dry filtration dust removal device in 2017, demonstrating a dust removal efficiency of 97.86% for respirable dust in field testing. They further conducted experimental studies on the filtration performance of filter media in different humid environments to investigate their application limitations [108]. Xu [109] designed a dry dust collector with a dust removal efficiency of 99.6% using a chemical fiber with high flame retardancy after antistatic treatment. Chen et al. [110], in 2022, designed a horizontal film-coated flat bag dust collector with PTFE filter material, which achieved a dust reduction of 98.95% for respirable dust. Overall, the dust removal efficiency of dry filtration dust collectors in conventional environments can reach 98–99% for total dust and 95% for respirable dust.

4.2. Wet Dust Collectors for Mines

Wet dust collectors use water or other liquids to interact with dusty air. The interaction occurs through liquid droplets, liquid films, or liquid bubbles (Figure 6), which collide and coagulate with dust particles, separating them from the air [111].

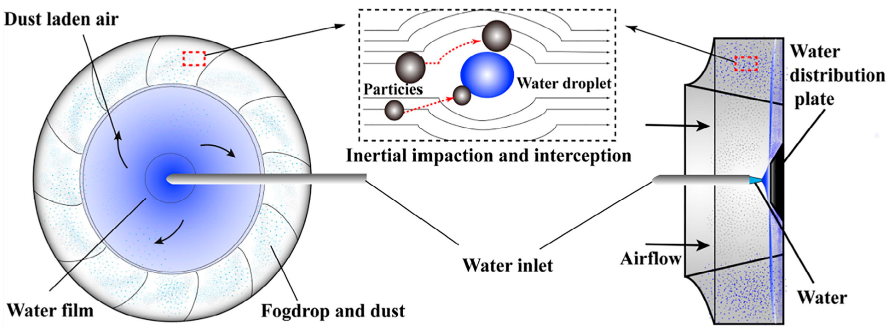

Figure 6. Dust removal mechanism of wet dust collectors for mining. Reproduced with permission from Jin, Z.J., etc., journal "*Advanced Power Technology*"; published by Elsevier, 2022 [112].

Wet dust collectors have a low risk of explosion and can handle high-temperature, flammable, and explosive gases. Their total dust removal efficiency can generally reach over 90%. Due to effective secondary dust prevention, they can also have a compact design to save space and a higher dust removal efficiency [112]. Wet dust collectors have been used underground in China since the 1950s. Some domestic wet dust collectors have been developed in recent decades, with models such as MLC, JTC, KGC, and others [113]. Current research in China focuses on enhancing dust removal efficiency, reducing equipment size, and minimizing noise in mining wet dust collectors. These efforts aim to improve equipment performance and meet environmental protection requirements.

The structure of a wet dust collector can be modified to improve its dust removal performance. Liu et al. [114] designed and placed a manifold inside a wet centrifugal dust collector and found that it helped to accelerate the centrifugal velocity and form a stable flow field, enhancing the removal of respirable dust. Hu et al. [115] modified the inclination angle of the metal filter mesh in a wet scrubber to improve its efficiency. Li et al. [116] studied the gas–liquid coupling condition inside a throttling-type water curtain dust collector. They adjusted the height of the contact cavity and the throttling intensity to improve its dust removal. Guan et al. [117] used a centrifugal KCS1000D wet dust removal fan and digging equipment to create an integrated dust removal system in the digging face of the Shendong Mine, achieving a dust reduction efficiency of over 95%. Zhu et al. [118] designed a double Y-type filter plate for a wet dust collector, increasing the dust removal efficiency to a maximum of 96.54%. In addition, some specific schemes can also be applied to wet dust collectors for their efficiency, including the continuous film-forming liquid membrane filtration scheme [119], the combination scheme of a centrifugal impeller and cylindrical casing [120], and the scheme of continuous formation and breaking of liquid film between chord grids [121]. These schemes have been found to significantly enhance dust removal.

Reducing the size of the wet dust collector can save space underground. Jiang et al. [122] developed a compact and lightweight wet dust collector, which achieved a removal efficiency of over 94% for respirable dust. Hu [123] designed a unique impeller that ensures high dust removal efficiency while reducing the equipment's volume. The dust removal efficiency of this dust collector for total dust and respirable dust was 95.8% and 88.6%, respectively. Hu [124] developed a compact and easily installable wet dust collector that utilizes impeller atomization instead of nozzle atomization. The dust collector measured only 2 m in length and 0.98 m in diameter, yet it could process dusty air of 550 m^3/min and have a total dust removal efficiency of over 96.3%.

As the primary noise source in wet dust collectors, fan noise must also be addressed. Researchers have designed and applied various methods and devices to reduce the fan noise. Li et al. [125] opened holes in the blades to ensure a more stable flow field inside the dust collector, which reduced the running noise from 119 dB to 92 dB. Deng [126] modified the structural layout of the fan guide vane to optimize the spraying unit, which achieved a 16.5% decrease in overall machine noise. Moreover, Lu [127] effectively reduced the noise generated by the dust collector by implementing multiple sets of sound-absorbing partitions.

5. Limitations and Prospects

5.1. Limitations and Solutions

Coal mine dust prevention and control technology has been effective in dust removal, but it still faces some problems and limitations.

Coal-seam water injection faces challenges when dealing with low-porosity coal and resistant coal seams. Future research should focus on developing water injection technology and equipment specifically designed for low-porosity and water-resistant coal seams. Wet rock drilling technology relies heavily on water sources, requiring specific water supply pressure for dust suppression. Optimizing drilling parameters and fluid composition and designing water-saving drilling plans are essential to address this. Water-sealed blasting requires waterproof explosives and detonators and has an extensive explosion range. Developing stable, waterproof blasting materials and optimizing the charging structure and blasting parameters to ensure safety during the operation process are crucial. Dust suppression technologies cannot thoroughly solve the dust problems, necessitating additional dust reduction strategies.

The droplets produced by spray dust reduction in a complex environment vary significantly, leading to unstable atomization effects and subsequently affecting the respirable dust removal efficiency. Further analysis of the atomization process and developing nozzles that offer more consistent atomization are crucial. Moreover, the prolonged suspension of water droplets and foam in the air during the process of spray dust reduction and foam dust removal can impact ambient temperature, humidity, and operator visibility, potentially compromising the safety of underground operations. Prolonged exposure of workers to dust suppressants and other chemicals through skin contact and inhalation poses health risks. Therefore, it is imperative to explore recovery and post-treatment methods for spray droplets and foam, as well as the development of environmental protection additives and foaming agents.

The dust removal efficiency of dry inertial dust collectors and dry cyclone dust collectors for respirable dust needs further improvement. Dry filter dust collectors are unsuitable for handling high-humidity air. It is necessary to design an air duct structure with higher efficiency in capturing respirable dust and develop filter cartridges and media to ensure dust removal efficiency in high-humidity environments. Moreover, dry dust collectors used in mining face challenges such as having a large volume and high maintenance costs. Future studies should optimize the structure, effectively utilize its internal space, and reduce space and maintenance costs.

Wet dust collectors used in mining operations rely on a consistent water supply, which poses challenges in water-deficient areas. Moreover, these collectors must be paired with a wastewater treatment system that can manage the same volume, as failing to treat the waste liquid can result in secondary pollution. This study suggests that future investigations should enhance dust capture and incorporate new additives to boost efficiency. Furthermore, developing a more effective waste liquid treatment subsystem can enhance the equipment's capacity to treat waste liquid and decrease liquid waste pollution.

5.2. Prospects of Dust Prevention and Control Technology

Besides the above developments, new technologies can be introduced. Considering the high-humidity environment underground, vapor heterogeneous condensation technology can be applied as a pretreatment for respirable dust to make it grow larger and easier to remove.

In a supersaturated steam environment, vapor tends to condense on respirable dust particles to form condensation nuclei, resulting in an increase in particle size and mass through continuous condensation (Figure 7). Vapor heterogeneous condensation technology is commonly used as a pre-conditioning method to remove fine particles in applications such as wet desulfurization and wet dust removal. The key principle involves creating a supersaturated steam environment where heterogeneous vapor condensation occurs on the dust surface to create larger particles. The combined effects of diffusion and thermal swimming facilitate the migration and collision of particles, ultimately resulting in the condensation and growth of fine particles [128].

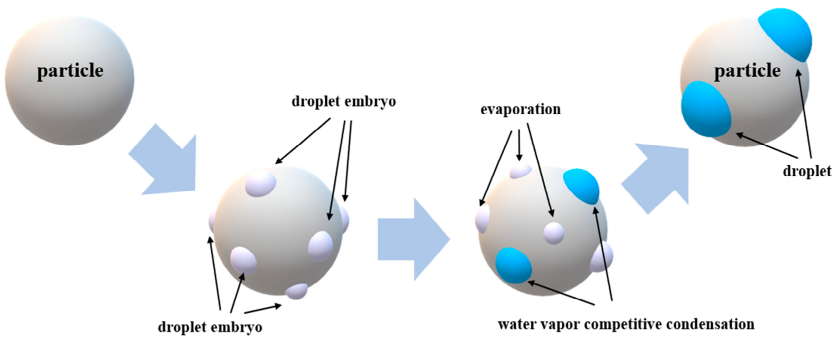

Figure 7. Water vapor condenses on the surface of particles.

In 1951, Schauer discovered that using steam to condense on the surface of particles is one of the most effective measures to promote the increase in ultrafine particles. In 1974, Calvert et al. attempted to achieve supersaturation by adding steam to the exhaust gas to promote the condensation and growth of iron oxide particles, and used a tower scrubber to remove them, achieving good results [128]. Subsequently, some researchers utilized steam phase change to remove respirable particulate matter. Bolota [129] designed a process that first condenses and grows submicron particles in saturated steam, and then removes them using an electrostatic precipitator. This scheme can achieve a dust removal efficiency of 90–95% for particles with an average particle size of 66 nm. Heidenreich theoretically analyzed the effects of conditions such as steam supersaturation, particle concentration, and operating temperature on particle nucleation performance and condensation growth, and found that under optimal environmental conditions, the dust removal efficiency can reach over 90% [128]. The above research shows that the vapor heterogeneous condensation technology can achieve good results in respirable particle removal.

Coal mines experience temperatures ranging from 25 to 40 °C and relative humidity levels of 80–100%. These temperature and humidity conditions provide an opportunity to create a supersaturated water vapor field to improve respirable dust removal through vapor condensation technology. Therefore, through adequate research and optimization, vapor condensation technology is a promising approach for dealing with respirable dust when coupled with a wet dust collector.

6. Conclusions

Dust control technologies in underground coal mines in China are classified into three categories: dust suppression technology, open-space dust reduction technology, and mine dust collector technology. This article reviews their working principles, performance characteristics, and research progress. Finally, their limitations and challenges were analyzed, and future research prospects were presented. The main findings of this study are as follows:

(1) Coal-seam water injection can generally reduce the production of about 60% of total dust during mining. However, the effect is unstable and significantly affected by the properties of the coal body and environmental conditions. The dust removal efficiency is influenced by the ability of water to wet coal and the effect of water injection. The ability to wet coal with water can be improved mainly by adding surfactants to water or using magnetized water. In addition, optimizing water injection parameters, adding surfactants to the fracturing fluid, and using carbon dioxide cold immersion can improve the effectiveness of coal-seam water injection.

(2) Wet rock drilling can effectively reduce dust generation during drilling but requires stable water sources and high-pressure equipment. The dust suppression efficiency of wet drilling can be improved by using magnetized water or adding surfactants, using substances such as foam, or optimizing water supply strategies.

(3) Water-seal blasting can generally achieve a total dust suppression efficiency of 50–70%, but explosives and detonators with good waterproof performance are required during use. Optimizing the water-seal blasting process in terms of charge quantity, charge structure, and water-seal height can give it a more stable dust suppression effect.

(4) The dedusting rate of spray dust removal on the total dust can reach 50–95%, but the dedusting rate on the respirable dust is low. The current research shows that using magnetized water or adding a surfactant or other liquid modification methods, and optimizing spray parameters, can increase dust removal efficiency by 10–40% and 5–10%, respectively. In addition, spray dust reduction also faces problems that may pollute the underground environment and endanger the health of operators.

(5) Under appropriate conditions, the dedusting efficiency of foam dedusting for total and respirable dust can reach 95% and 85%, respectively, and the water consumption is less than that of spray dedusting. However, it also easily pollutes the underground working environment and endangers workers' health. In addition, the instability of the foaming process may affect its dust removal effect. Optimizing the composition of the foaming agent can effectively improve the dust collection performance of the foam.

(6) Dry dust collectors for mining without filter materials can be divided into inertial and cyclone dust collectors, with a total dust removal efficiency generally of 80–95%. The dry dust collector with a filter material for mining is a filter dust collector, and its dust removal efficiency for both total dust and respirable dust can reach over 95%. Mining dry dust collectors have high dust removal efficiency but are not suitable for handling high-humidity air, and they have a large volume and high maintenance costs.
(7) Wet dust collectors for mining can treat air with high moisture content, and the total dust removal efficiency can generally reach over 90%. However, they require a stable water source during operation. In addition, they must be equipped with a suitable wastewater treatment system; otherwise, this approach will lead to secondary pollution. The current research mainly focuses on improving dust removal efficiency and meeting environmental protection needs.
(8) Vapor heterogeneous condensation technology has demonstrated extensive utility in eliminating fine particles. Considering the elevated temperatures and humidity prevalent in underground environments, this technology is believed to be more than suitable for enhancing respirable dust growth and removal when coupled with some wet dust removal technologies.

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