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A Study on Dust-Control Technology Used for Large Mining Heights Based on the Optimization Design of a Tracking Spray Nozzle

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Abstract: Intense cutting-induced dust production in fully mechanized mining faces (FMMFs) with large mining heights produces a high amount of dust that is difficult to capture and severely affects the working environment, threatening the health of occupational staff. The effective spray range and atomization performance of tracking sprays are counteracted by the influences of the mine's height and ventilation airflow in FMMFs. Thus, optimizing the spray's parameters and relationship between the effective spray range and atomization performance to reduce dust levels is the main priority of dust-control techniques. In this study, a new swirl-core atomization nozzle is developed based on fluid mechanics and the solid–liquid coalescence mechanism. The liquid generates a circumferential velocity when passing through the swirl core, which considerably increases the droplet breaking power and reduces the droplet cohesion factor, achieving a remarkable atomization effect. The spray angle of the new nozzle is 57°, which is 80.9% greater than the GZPW-16 mine-use nozzle (31.5°); the effective spray range increases from 5.2 to 5.9 m; and the spray's mist saturation is significantly better than the GZPW-16 mine-use nozzle. Under different test pressures, the particle size range of the droplets produced by the new nozzle and dust particles on site satisfied the best synergy of droplet–dust coalescence. The total and respirable dust-reduction rates were 78% and 75.1%, respectively, which were 42% and 65% higher than those of the original nozzle. The new nozzle effectively improves the efficiency of the single dust-control technique of the tracking spray, which is significant for the dust-prevention and -control technology of FMMFs with large mining heights.

Keywords: large mining height; fully mechanized mining face; tracking spray; swirl atomization nozzle

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1. Introduction

China is the world's largest coal producer and consumer. At present, coal is the main energy source in China and will still serve as its basic energy source in 2050 [1–4]. In recent years, large coal mines in Shanxi, Shaanxi, and Inner Mongolia have been put into operation, and fully mechanized faces (FMMFs) with large mining heights contribute to fulfilling the overall target of annual production in these mines [5,6]. However, the increase in mining scale and intensity is accompanied by an increasing amount and intensity of dust being produced in underground coal mines. According to the field research, in the absence of dust-control measures, the time-weighted concentrations of total and respirable dust concentrations in the main working areas can reach 400–900 and 300–500 mg/m^3, respectively, when coal cutting and other movements are conducted together. This severely impacts the safety in coal mines and threatens the occupational health of the coal workers. By the end of 2021, there were 915,000 reported cases of occupational pneumoconiosis in China, including 465,000 deaths [7–9]. In addition, a total of 15,407 new cases of occupational diseases, including 11,809 cases (77.65%) of occupational pneumoconiosis, were reported each year [10].

Existing mine-dust-control technologies include wet-spray dust reduction and dry dust, ventilation dust, and electrostatic dust removals. Among them, the dust-reduction spray is one of the most common and effective methods used [11]. In order to improve the efficiency of the dust-reduction spray in FMMFs and enhance the underground air quality, scholars have designed and optimized various dust-reduction facilities and spray dust-settling systems based on theoretical analyses and field tests [12–14]. Zhou [15] optimized the arrangement of a hydraulic support spray group by improving the spray of a front-probe beam by changing its direction, which was perpendicular to the coal mine wall. Nie et al. [16] tested a negative-pressure secondary-spray dust-reduction device that can suck and purify part of the dust-containing air stream, while reducing the dust passing through the nozzle. Guo et al. [17] analyzed the characteristics of dust produced by coal cutting using a shearer in FMMFs with large mining heights. Zhang [18] proposed three-dimensional dust-reduction technology for FMMFs with large mining heights by integrating efficient spray and automatic dust-reduction technology. Wang et al. [19] optimized the design of inter-support spraying technology in the FMMFs by changing the spray direction to face perpendicular to the coal mine wall. Ma [20] designed a new tracking-spray dust-reduction system based on the STM32 core processor, which can automatically reduce dust produced during the coal mining processing. Peng et al. [21,22] developed a blast-spray synergistic dust collector mounted on a hydraulic support, with the aim of reducing dust pollution in FMMFs, where the high-speed airflow traveling in the same direction as the dust-collector spray improves its range and produces high-quality spray and airflow curtains. Xu et al. [23] conducted numerical simulations of different spray parameters for a hydraulic-support-spray dust-suppression device; the simulation results revealed a spray pressure of 8 MPa and a nozzle size of 2.4 mm, and the spray field concentration in more than 70% of the target area was larger than 0.04 kg/m^2. Nie Wen [24] researched the inter-support spray and dust-removal technology used in FMMFs according to spraying and dust-removal mechanisms. Zhou [25] conducted a simulation analysis for the dust-droplet field-distribution characteristics of dust sources of the shifting support of an FMMF, which can effectively improve the control of the dust produced by the shifting support of the working face. Considering the existing deficiencies (e.g., the unreasonable selection of nozzles and failure of water pressure to meet the dust-reduction demand) of existing tracking-spray systems, Gan et al. [26] selected a nozzle that could produce a three-dimensional conical spray and increased the spray pressure. Zhi [27] introduced new technology for dust source tracking and reduction for automatic shearers. Bu [28] designed a set of air–water linkage automatic-spray dust-removal devices, whose spray could be turned on automatically, and optimized the original atomization nozzle. By conducting a simulation study for a swirl-nozzle liquid medium shifting from the continuous to particulate phase using a volume of fluid (VOF) model and discrete phase model (DPM), Faeth Gm [29] obtained the intrinsic mechanisms of primary and secondary atomizations of liquid. Wei [30] optimized the design of parameters for the tracking-spray dust-reduction system. Yang [31] installed two sets of negative-pressure secondary-dust collectors on the shearer body, which were placed on the front and rear drums. Ultimately, the inter-support and negative-pressure secondary-dust-collector sprays turned on automatically, at the same time, thus significantly enhancing [32–34] the dust-reduction efficiency.

However, the following deficiencies still exist when the field of spray for ordinary mining faces is applied to FMMFs with large mining heights [35]: (1) the shearer drums and hydraulic supports in FMMFs with large mining heights are larger and higher than those in ordinary coal mines; therefore, it is difficult for the atomization nozzles commonly used in ordinary mining faces to meet the distance requirements of large mining faces. Moreover, there is greater dust production in large mines, which requires a higher mist field concentration. (2) As large mining heights have larger work spaces, if the nozzle's spraying position and angle remain the same as those in ordinary mining faces, it is difficult for the mist field formed to cover the high concentration of dust in the working face, for which it is difficult to achieve the effect of closed dust-control measures. (3) As the structure of the on-site mining nozzle is a straight-through hole, the liquid flow is atomized by using the speed difference between the liquid and ambient air to generate an aerodynamic force. Since the liquid stream crushing power is only air power, it is difficult to provide sufficient energy for liquid stream crushing; therefore, the atomization effect is limited.

In summary, based on the atomization and control range of the tracking spray and its effective range in FMMFs with large mining heights, it is particularly important to design and develop a long-distance efficient nozzle suitable for the dust-reduction characteristics of hydraulic support areas in FMMFs with large mining heights, which is the key to improving the dust-reduction efficiency of the supports.

2. Optimization Design for Nozzle Structure of Support Tracking Spray

2.1. Development of a Long-Distance, Efficient Wear-Resistant Nozzle

Considering the status of a support tracking spray in FMMFs with large mining heights and the dust particle size during coal cutting, a new type of long-distance, efficient wear-resistant nozzle was developed on the basis of the types and structures of dust-reduction nozzles commonly used in coal mines [36–40]. Together with Changyuan Spray Technology in Dongguan, China, we developed a new type of long-distance wear-resistant nozzle, whose physical diagram and internal structure are displayed in Figure 1. The new nozzle adopted an internal swirl core. After passing through the swirl core, the liquid rotates in the swirl chamber under the action of its circumferential velocity before being ejected from the nozzle. The nozzle takes full advantage of inertial forces, where the centrifugal force caused by the high-speed rotation in the nozzle can effectively promote the initial atomization, while the flow field of the liquid is altered through the constraints of the internal structure [41]. However, the centrifugal nozzle is large, which causes a rather lower resistance to the liquid than the commonly used nozzle; therefore, the liquid is ejected at a high speed. As the increased inertial force does not cause a weakening of aerodynamic forces, the liquid is ejected in the form of a thin film. Moreover, since such a film can reduce the surface tension force within the liquid cross-section, the ability of the liquid film to resist inertial and aerodynamic forces is greatly diminished.

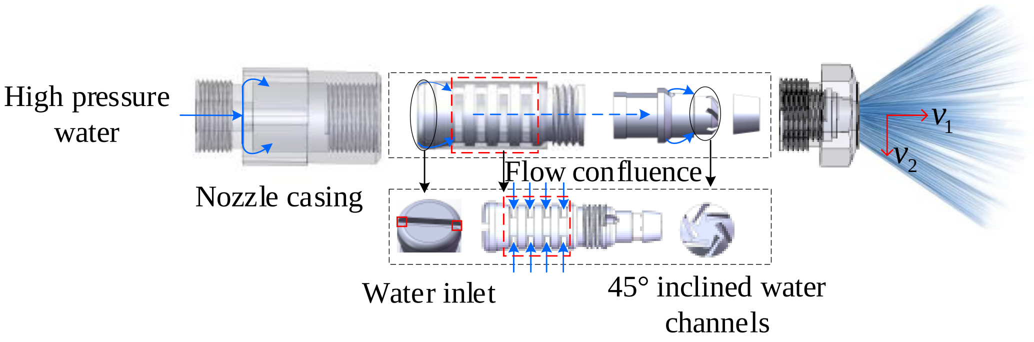


Figure 1. Inner structure of the new nozzle.

The working principle of the new nozzle is as follows: after the pressurized water enters the nozzle, it is first filtered by the strainer and then flows into Swirl Core 2 for a full swirl. At this time, the high-pressure water, with a high circumferential velocity, passes through the two water outlets of the swirl core, and then the two converge at the end of Swirl Core Component 4 and impact each other to further increase the circumferential and axial velocities of the water. Finally, the water is ejected through six of the 45° inclined flow channels of the swirl core. The centrifugal force caused by the high-speed rotation in the nozzle can effectively improve the initial atomization of the water pressure. Meanwhile, the inertial and aerodynamic forces of the sprayed-fluid micro-cluster can effectively overcome the liquid internal force, promoting a re-atomization of droplets.

Based on the principle of aerodynamics, the reason why the new nozzle's atomized droplets can capture the dust flying in the air can be explained as follows: when the dust-containing airflow bypasses the atomized droplets, the droplets capture dust particles of different sizes through inertial collision, interception, coalescence, and diffusion. When the dust-containing airflow meets the droplets during its motion, it changes its direction to bypass them. Fine-dust particles can bypass the droplets with the airflow, while the large-sized particles and mass cannot perform this along the flow line as a result of their greater inertia. Instead, they have to maintain their original direction of motion, collide with, and be captured by the droplets. Moreover, the dust particles close to the atomized droplets perform a bypassing motion along the flow line because they are of a certain volume. When the distance between the flow line where the center of mass of the dust particle is located and the droplet is less than the radius of the dust particle, the dust particle comes into contact with the droplet and is thus intercepted by and attached to the droplet, which is called interception capture. The wet dust-capture mechanisms of the new nozzle are mainly inertial collision and interception capture.

2.2. Analysis of the Atomization Performance of the New Nozzle Based on Laboratory Tests

The new and GZPW-16 mine-use nozzles, whose internal structures are different, were selected as the experimental nozzles. Their parameters are listed in Table 1.

Table 1. Parameters of the two types of nozzles.

Type	Size/mm	Material	Swirl-Core Structure
New nozzle	1.6	Copper	No swirl core
GZPW-16 mine-use nozzle	1.6	Stainless steel	Multi-fluid circle structure

Three groups of experiments were designed for the nozzle's atomization performance. The first group used flow meters to test the nozzle flow rate for water pressures of 3, 4, 5, 6, and 7 MPa; the second used a high-definition camera to take pictures of the stable-spray state during different spray pressures (3–7 MPa) and obtained the effective range and atomization angle of the nozzle spray through the image-processing technique; the third, based on the nozzle atomization characteristics experimental platform, measured two types of nozzles' mist particle sizes during different spray pressures. The three groups of experiments were combined to compare the spray performances of the two types of nozzles.

As shown in Figure 2, the test system for nozzle atomization characteristics comprised an inlet pipe, flow meter, throttle valve, large-capacity water tank, booster pump, pressure gauge, high-pressure pipeline, and nozzle base. During the test, the particle size of the droplets was measured by the DP-O2 laser particle size analyzer (Hongliulin Coal Mine, Shanxi, China).

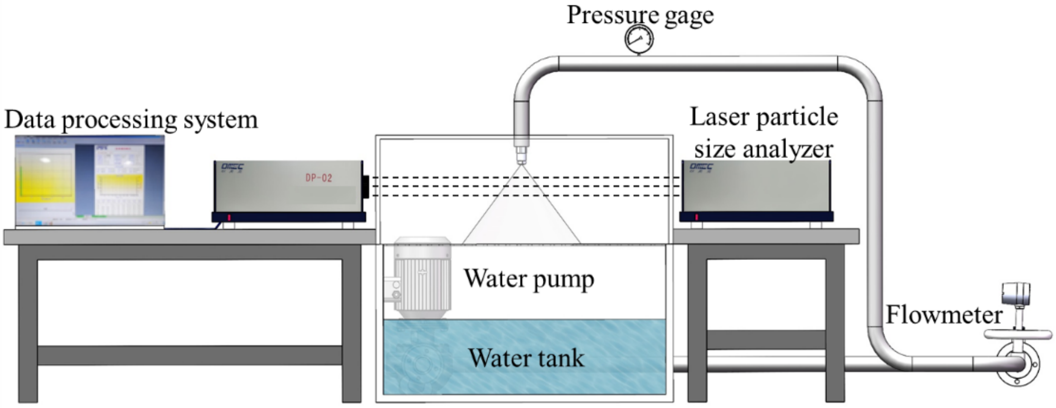


Figure 2. Test system for nozzle atomization characteristics.

3. Experimental Results and Analysis of Atomization Characteristics of Nozzles

The commonly measured water pressure of the support tracking spray in the FMMF with a large mining height was 6 MPa. Atomization performance tests were conducted on the GZPW-16 mine-use and new nozzles under 3–7 MPa of water pressure. The test data are presented in Table 2.

Table 2. Test data of the two types of nozzles.

Nozzle	Spray Pressure (MPa)	Spray Flow Rate (L/min)	Effective Spray Range (m)	Atomization Angle (°)
New nozzle	3.0	5.52	3.90	62.7
	4.0	6.47	4.40	60.9
	5.0	7.08	4.90	58.3
	6.0	7.95	5.50	57.6
	7.0	8.46	5.90	55.2
GZPW-16 mine-use nozzle	3.0	5.42	3.80	52.5
	4.0	6.24	4.20	50.7
	5.0	6.92	4.50	48.2
	6.0	7.55	4.80	47.2
	7.0	8.19	5.20	44.2

As shown in Table 2, as the spray pressure increases for both types of nozzles, the effective spray range and flow rate increase, while the atomization angle decreases. This can be explained as follows: as the spray pressure increases, the droplets acquire increased spray kinetic energy in both the axial and radial directions; therefore, they are able to reach a longer distance. However, because the energy increment in the radial direction is much lower than that in the axial direction, the droplets gradually concentrate in the axial direction. Ultimately, the atomization angle decreases with the increase in the spray pressure.

A Further comparison reveals that under the same spray pressure, the effective spray range and atomization angle of the new nozzle are both greater than those of the GZPW-16 mine-use nozzle, while their spray flow rates are similar. This means that the new nozzle presents a better atomization performance than the mine-use nozzle, and it can form a mist wall in the cross-section of the working face and realize the local closure of the shearer.

Based on the test of the nozzle atomization performance, the particle sizes of droplets from the two types of nozzles were measured by adopting the DP-02 spray laser-particle size analyzer. The laser measuring point was located at the cross-section 1 m from the nozzle outlet. The measurement was repeated three times, and the measurement results of the droplets' characteristic and average particle sizes are presented in Table 3, where D_{10} indicates that the total volume of the droplets smaller than this size is 10% of the total volume of all droplets, and other characteristic particle sizes have the same representation as D_{10}.

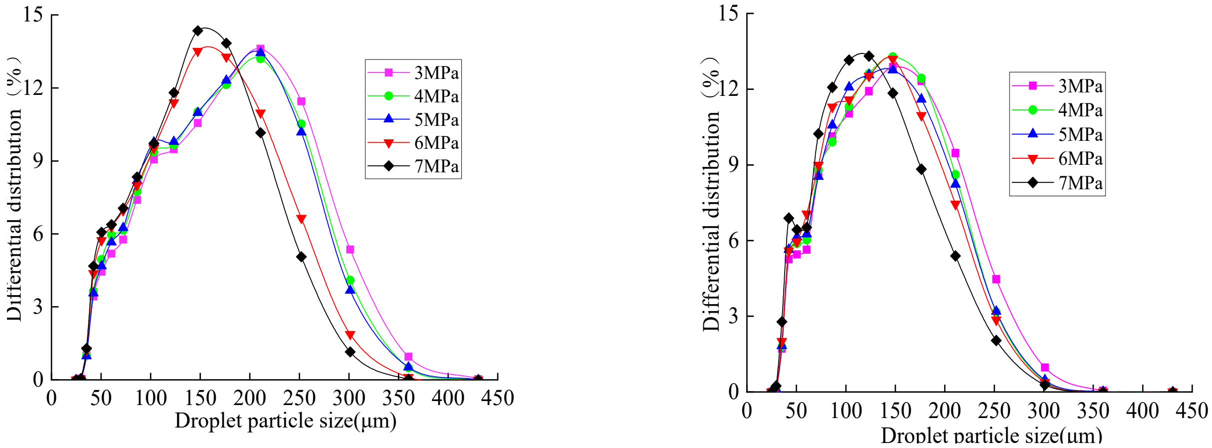
Table 3. Characteristic particle sizes of the two types of nozzles.

Nozzle	Spray Pressure (MPa)	D_{10}/μm	D_{25}/μm	D_{50}/μm	D_{75}/μm	D_{90}/μm
New nozzle	3.0	46.11	69.89	106.73	152.25	192.67
	4.0	45.08	67.82	104.1	146.86	183.78
	5.0	45.01	67.37	101.56	144.51	183.08
	6.0	44.91	66.53	101.49	143.88	180.27
	7.0	42.43	63.01	92.38	129.27	167.91
GZPW-16 mine-use nozzle	3.0	52.74	82.43	132.96	191.76	235.12
	4.0	51.26	78.36	126.75	184.49	227.52
	5.0	49.07	73.07	121.88	173.07	210.29
	6.0	48.45	72.88	117.34	163.96	205.23
	7.0	47.57	71.46	114.77	157.57	196.26

According to Table 3, as the spray pressure increases from 3 to 7 MPa, for the GZPW-16 mine-use nozzle, the particle size of the droplets whose cumulative numbers account for 90% decreases from 235.12 to 196.26 μm by 16.5%, and that for droplets whose cumulative numbers account for 75% decreases from 191.76 to 157.57 μm by 17.8%. For the new nozzle, the particle size of droplets whose cumulative number accounts for 90% decreases from 192.67 to 167.91 μm by 12.9%, and those of droplets whose cumulative number accounts for 75% decreases from 152.25 to 129.27 μm by 15.1%.

The characteristic and average particle sizes of both types of nozzles decrease with the increase in spray pressure. This was mainly attributed to the fact that the increased spray pressure can create more kinetic energy, which facilitates the spray atomization effect and produces smaller droplets.

The data in Figure 3 indicate that, under different spray pressures, for the GZPW-16 min-use nozzle, the droplets with a particle size of 147 μm account for the highest percentage (12.1% on average). As the spray pressure increases, the percentage of droplets with a particle size of 0–120 μm increases from 45.85% to 55.40%. For the new nozzle, the droplets with a particle size of 124 μm account for the highest percentage (12.6% on average). With the increase in the spray pressure, the percentage of droplets with a particle size of 0–120 μm increases from 59.85% to 71.62%. For the spray pressure of 7 MPa, the new nozzle was 16.22% stronger than the GZPW-16 min-use nozzle with respect to the percentage of droplets with a particle size of 0–120 μm. From the solid–liquid coalescence mechanism, droplets with this particle size are more likely to capture dust particles; therefore, the new nozzle was superior to the GZPW-16 min-use nozzle for dust-reduction performance under the same spray-pressure condition.



(**a**) (**b**)

Figure 3. Droplet size distribution of the nozzles. (**a**) GZPW-16 mine-use nozzle; (**b**) New nozzle.

In summary, under the same spray-pressure condition, both the effective spray range and atomization angle of the new nozzle were greater than those of the GZPW-16 mine-use nozzle, which was more conducive to the formation of horizontal and vertical mist curtains at a wide spray range. Meanwhile, the new nozzle corresponded to producing a higher percentage of droplets with a particle size of 0–120 μm, highlighting its better atomization performance.

4. Practical Applications

Our experimental site was located in the Hongliulin Coal Mine, Shanxi, China. The 25212 FMMFs with a large mining height has a designed strike length of 3082 m, a dip length of 348 m, a cross-sectional area of 45 m^2, an average coal thickness of 5.7 m, a shearer cutting speed of 6 m/min, a shearer drum diameter of 3.5 m, and a designed mining height of 5.6 m. Some other parameters of the working area included airflow speed: 1.2 m/s, dry bulb temperature: 22 °C, relative humidity: 89%, and air volume: 2520 m^3/min. It is supported by a total of 173 ZY18000/29.5/63D two-legged shield hydraulic supports (Figure 4). The present tracking spray nozzles were all GZPW-16 six-hole nozzles, four of which were installed at each support.

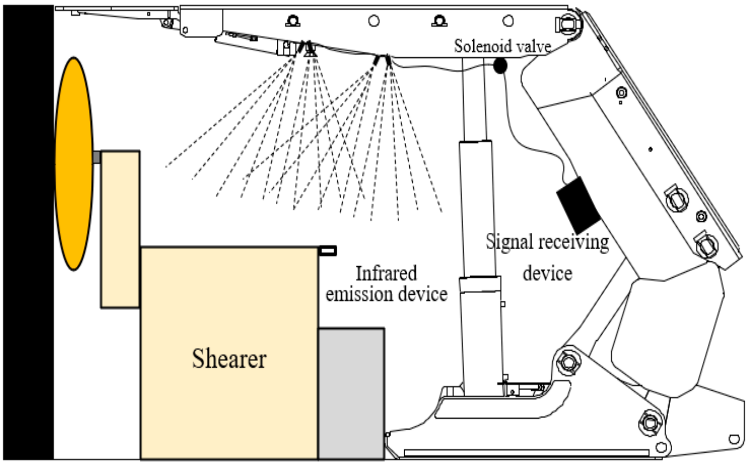


Figure 4. Schematic diagram of tracking spray device installation.

The dust-control and -reduction processes of the support tracking spray in the 25212 FMMF was as follows: when the shearer was cutting the coal, the tracking spray at 3 and 4 hydraulic supports in front of the drum on the windward side and at 3 and 4 hydraulic supports behind the drum on the leeward side were turned on. The duration from the start to the end of spraying was 4 s.

The new long-distance efficient wear-resistant nozzles were tested in the FMMFs in Hongliulin Coal Mine (Figure 5). The atomization angle of each GZPW-16 mine-use nozzle was 31.5°. With the large, uncovered area between the two nozzles, the spray failed to completely cover the cross-section of the mining face to form a mist curtain wall; the mist in the nozzle atomization field was thin and could be penetrated by the line of sight, indicating that the nozzle atomization effect and coverage of the cross-section were poor. In contrast, the atomization angle of each new nozzle was larger (57°), which enabled the spray to cover a large area and effectively form a mist curtain in the cross-section area. As for the atomization effect, compared with the thin mist formed by the GZPW-16 mine-use nozzle, the mist formed by the new nozzle was more saturated and could not be easily seen through. Thus, the atomization performance and local closed mist curtain produced by the new nozzle were much better than those produced by the GZPW-16 mine-use nozzle.

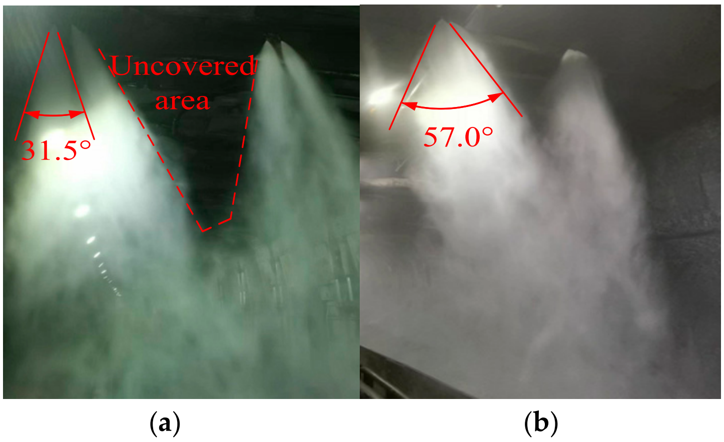


Figure 5. Comparison of tracking spray atomization performance and closure effect. (**a**) GZPW-16 min-use nozzle; (**b**) New nozzle.

According to the characteristics of dust production and the location of coal workers in the 25212 FMMFs, in total, we tested six dust-concentration points numbered A–F; among them, point A was set 15 m from the inlet airway, point B 15 m from the return airway, points C and D on the leeward side of the tracking spray, point E 5 m from the downwind side of the shift frame, and point F at the coal miner driver. The arrangement of the measuring points refers to the field dust-concentration determination requirements specified by the national and industry standards: "Method of Determination of Dust in Air at Workplaces" (GB5748-85) and "Method of Determination of Dust Concentration and Dispersion" (MT79-84). In addition, all data test points were determined based on the "Technical Specification for Comprehensive Control of Underground Dust in Coal Mines" (AQ1020-2006). The locations of the measuring points are presented in Figure 6.

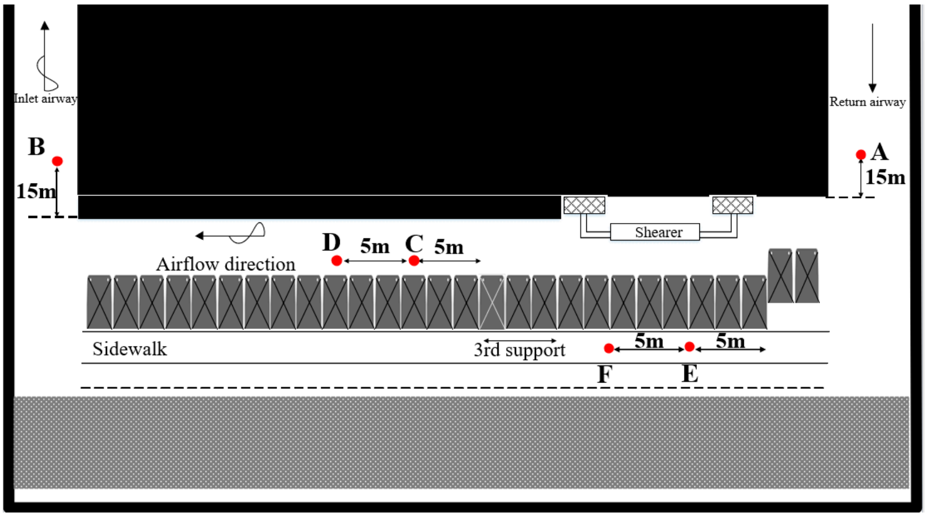


Figure 6. Layout of dust-concentration measuring points in the FMMFs.

The dust samples collected during the production in the FMMFs were measured by the Malvern laser-particle size analyzer. To ensure the accuracy of the results, four groups of parallel tests (a, b, c, and d) were conducted. In these tests, the dust particle size distribution, average particle size, median particle size, and other characteristic particle sizes were investigated. The results are presented in Figure 7.

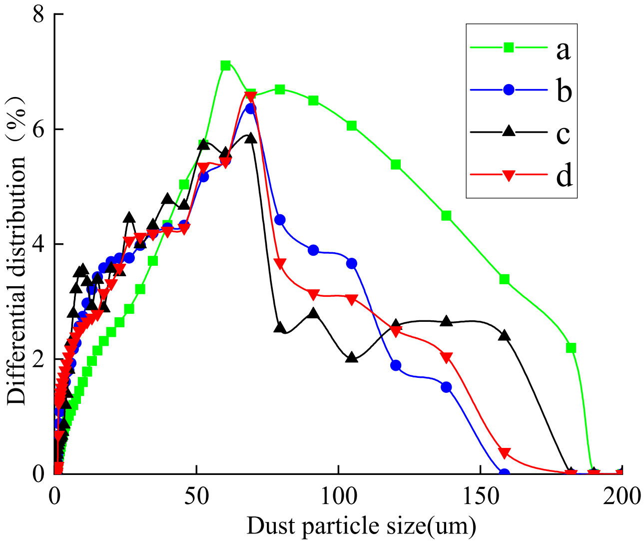


Figure 7. Dust particle size distribution of dust-containing air in the FMMFs.

According to the particle size distribution of dust-containing air in the FMMFs, in the four test groups, dust with a particle size of 30–60 µm was dominant, while dust with a particle size larger than 70 µm accounted for a relatively small proportion of the size, with the median particle size being 50 µm. Large dust particles settle, while small ones diffuse and are suspended in the air under the influence of the airflow. As mentioned in the previous section, when the spray pressure is 7 MPa, the particle size of the droplets produced by the new nozzle is mostly distributed in the range of 0–120 µm (71.62%). Based on the solid–liquid coalescence mechanism, the droplets in the FMMFs, which are of comparable particle sizes with the dust particles, are more likely to capture the dust particles when colliding with them, thus effectively promoting the dust-settling effect of the tracking spray.

In accordance with the production conditions in the FMMFs, the concentrations of total and respirable dust concentrations in different locations were determined using the membrane-filter method under the following three states: tracking spray turned off, tracking spray turned on, and new nozzle turned on. The results are presented in Table 4 and the data are illustrated in Figures 8 and 9.

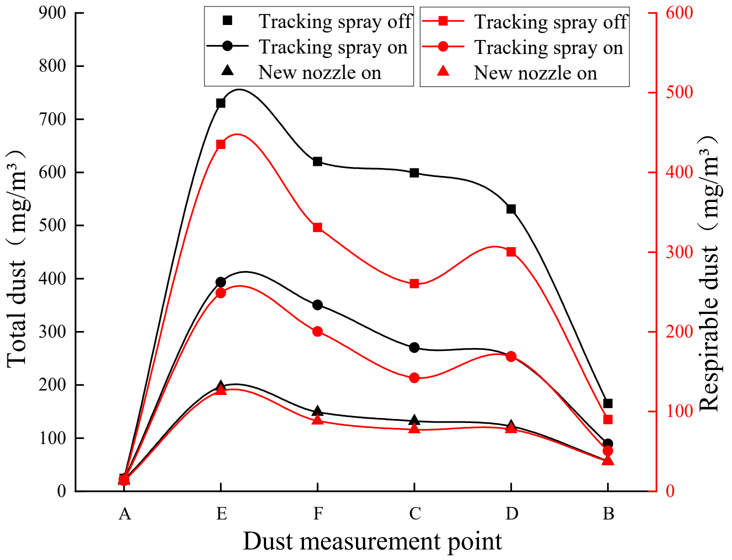


Figure 8. Dust concentrations in different states at measuring points in the FMMFs.

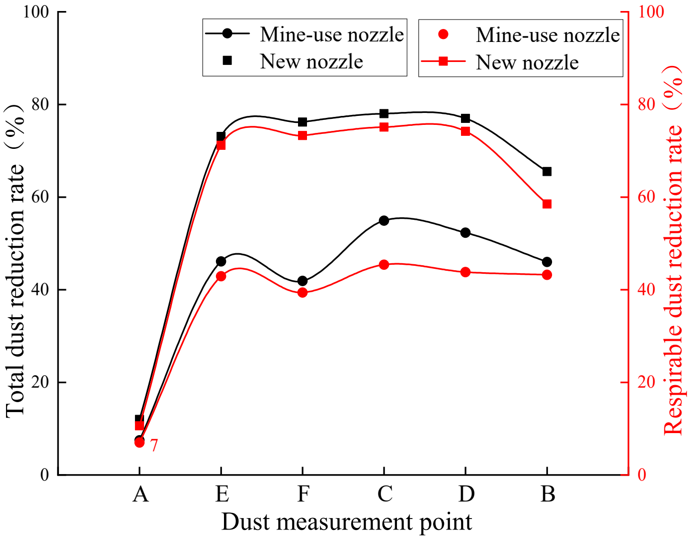


Figure 9. Dust-reduction rates for different nozzles at measuring points in the FMMFs.

Table 4. Distribution of dust concentrations along the FMMF.

Location **State**	**Dust Concentration/mg/m^3**	**A-15 m from the Inlet Airway**	**E-5 m on the Leeward Side of the Support**	**F-Driver of the Shearer**	**C-5 m on the Leeward Side of the Tracking Spray**	**D-10 m on the Leeward Side of the Tracking Spray**	**B-15 m from the Return Airway**
Tracking spray off	Total dust	24.1	730.2	620.5	599.1	530.9	165.1
	Respirable dust	14.2	435.1	330.8	310.3	300.2	89.9
Tracking spray on (GZPW-16 mine-use nozzle)	Total dust	22.3	393.4	360.5	270.3	253.5	89.1
	Dust reduction rate (%)	7.5	46.1	41.9	54.9	52.3	46
	Respirable dust	13.2	238.4	187.2	146.3	148.5	48.6
	Dust reduction rate (%)	7.0	45.2	43.4	54.6	51.5	45.9
Tracking spray on (new nozzle)	Total dust	21.2	196.6	148.9	131.8	122.1	56.9
	Dust reduction rate (%)	12.0	73.1	76.2	78.0	77	65.5
	Respirable dust	12.7	125.3	88.3	77.3	77.5	37.3
	Dust reduction rate (%)	10.6	71.2	73.3	75.1	74.2	58.5

When the tracking spray was turned off, the total dust concentrations at the measuring points all exceeded 500 mg/m^3, the maximum value being 730.2 mg/m^3, which was 182 times greater than the value specified in the *Coal Mine Safety Regulations* [42]. The respiratory dust concentrations all exceeded 260 mg/m^3, the maximum being 435.1 mg/m^3, which was 108 times greater than the specified value, as shown in Figure 8. The results suggest that, in the absence of dust-control measures, the dust concentration during the normal production of the FMMFs greatly exceeds the limit. After the original tracking spray is turned on, both the total and respirable dust concentrations decrease. In Figure 9, the highest total dust and respirable dust-reduction rates are 54.9% and 43.4%, respectively. After the new nozzle tracking spray is turned on, the total dust and respirable dust concentrations decreases remarkably. The highest total dust and respirable dust-reduction rates increase further from 54.9% and 43.4% to 78% and 75.1%, respectively. The on-site industrial test demonstrated that the new nozzle could effectively improve the efficiency of the single dust-control technique of the tracking spray. This was the key to solve the problem of the antagonism occurring between the effective spray range and atomization performance in FMMFs with large mining heights and is of great significance for creating comprehensive dust-prevention and -reduction technology in such FMMFs.

5. Conclusions

This study aimed to improve the unsatisfactory local, closed atomization effect of a tracking spray and overcoming the antagonism between the atomization effect/control and effective ranges of dust-control techniques in FMMFs with large mining heights. According to the nozzle atomization characteristics and solid–liquid coalescence mechanism, the nozzle structure of a tracking spray for FMMFs with large mining heights was optimized, and a field industrial test was conducted. The main conclusion were as follows:

(1) Based on the mechanism of high-pressure water atomization, the nozzle with a built-in swirl core that could generate a circumferential velocity was innovatively developed from two aspects, i.e., enhancing the destructive effect of the aerodynamic force on the liquid flow and reducing the resistance effect of the internal force of the liquid. The device gave full play to inertial and aerodynamic forces to break the liquid and, due to the role of the swirl core, the liquid was ejected in the form of a thin film, reducing the surface tension in the liquid-surface cross-section. In addition, all parts were ultra-fine polished, which effectively improved the corrosion resistance of the swirl core, decreased the friction between the swirl core and nozzle shell, and reduced the energy loss when the water passed through the swirl core. The experiment showed that, under the same spray-pressure conditions, the newly developed nozzle projected water over a long and effective distance, presenting an excellent atomization performance and a large atomization angle.

(2) Based on the range of the dust particle size distribution (30–60 μm) and the mechanism of dust captured by gas–liquid two-phase condensation, an optimization test design for the structural parameters of the long-distance high-efficiency nozzle was conducted. It was observed that, at a spray pressure of 6 MPa and a nozzle size of 1.6 mm, the droplet particle size distribution of the new nozzle mainly ranged from 0 to 120 μm, which can remarkably improve the droplets' dust particle-capture efficiency in FMMFs.

(3) Based on the industrial tests, the new nozzle had a high droplet density and an effective range that could cover FMMFs with large mining heights. Its spraying angle was 57°, which was 80.9% greater than that of the original nozzle (31.5°). After the new nozzle tracking spray was turned on, the dust removal efficiency was significantly improved, reaching a maximum of 78% for total dust and 75.1% for respiratory dust, which were 42% and 65% greater than those of the GZPW-16 mine-use nozzle spray, respectively. The application results suggest that its spraying performance, better than that of the GZPW-16 mine-use nozzle, is more conducive to the formation of a wide range of horizontal and vertical mist curtains.

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