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Engineering Application of Gas–Liquid Two-Phase Fine Water Mist Atomization for Dust Suppression Abstract

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A**bstract:** Respirable dust generated during fully mechanized coal mining poses a serious threat to occupational health and safe production. To overcome the limitations of conventional high-pressure water spray systems, a novel gas–liquid two-phase spray dust suppression technology was developed and applied at the 22410 fully mechanized longwall face of Halagou Coal Mine in the Shendong mining area. Based on an analysis of dust generation characteristics and the physicochemical properties of respirable coal dust at major emission sources, the spray systems at the crusher transfer point, inter-shield region, and return airway were systematically optimized in terms of nozzle type, quantity, and spatial arrangement, with the original high-pressure spray devices replaced by gas–liquid two-phase spray units. Field experiments under actual mining conditions were conducted, and continuous multi-point measurements of respirable dust concentrations were performed. The results indicate that, compared with the original system, the respirable dust reduction efficiency at the crusher transfer point increased by 26.0%, while respirable dust concentrations in the inter-shield region were reduced to 21.0–22.1% of their original levels, and the maximum reduction in the return airway reached 69.2%. The gas–liquid two-phase spray system exhibited superior atomization performance and significantly enhanced dust capture efficiency, particularly in large-space and high-airflow mining environments. These findings demonstrate that the optimized gas–liquid two-phase spray system can effectively reduce respirable dust concentrations across fully mechanized longwall faces, thereby mitigating occupational health risks and improving mine safety, and provide a practical and reliable engineering solution for respirable dust control in modern coal mining operations.

Keywords: Gas–liquid two-phase; Spray; Engineering application

1. Introduction

With the rapid development of China's economy, the demand for coal has increased sharply. China is the world's largest producer and consumer of coal, and the coal industry not only provides extensive employment opportunities but also plays a fundamental and pillar role in national economic development [1–3]. The country's energy resource endowment is characterized by coal abundance, oil scarcity, and limited natural gas, which fundamentally determines the dominant position of coal in the primary energy mix. Coal consumption accounts for more than 70% of total energy consumption and is projected to remain at approximately 60% by 2050. Consequently, coal mining continues to be of critical importance to the national economy [4–6]. However, intensive coal extraction activities generate large quantities of respirable dust, leading to severe dust pollution in mining environments. Long-term exposure to high concentrations of coal dust poses significant health risks to workers, including pneumoconiosis and other occupational respiratory diseases, thereby constituting a major challenge to safe and sustainable coal production [7–10].

In response to dust-related hazards in coal mining, extensive research has been conducted by domestic and international scholars, particularly in the areas of dust generation mechanisms, dust suppression materials and additives, spray atomization characteristics, and ventilation–spray coupling technologies. Significant progress has been made in understanding dust transport behavior and in developing laboratory-scale dust control methods. Nevertheless, notable limitations remain. Existing studies are predominantly theoretical or laboratory-based, while systematic investigations into engineering-oriented solutions and long-term field applications are relatively scarce. As a result, the effectiveness, adaptability, and stability of many proposed dust suppression technologies under complex on-site mining conditions have not been fully validated.

In view of these limitations, the present study adopts a combined approach of experimental analysis and field validation to investigate the engineering application of gas–liquid two-phase flow–driven fine water mist spraying. By integrating controlled laboratory experiments with on-site testing in real mining environments, this research aims to elucidate the atomization characteristics, dust capture mechanisms, and practical dust suppression performance of gas–liquid two-phase micro-mist systems, thereby providing a more reliable technical basis for effective dust control in coal mining operations.

2. Gas–liquid Two-phase spray dust suppression device

A novel gas–liquid two-phase spray device was designed, in which the internal nozzle structure incorporates a built-in throttling rod and an adjustable gas-orifice offset angle. The schematic of its working principle is shown in **Figure 1**. Water and compressed air enter the two-phase atomization nozzle through the water and air quick-connect inlets, respectively. The water first flows through a dedicated channel into a large chamber, where a throttling rod is installed. This component is designed to regulate and limit the water flow rate, thereby increasing the relative velocity between the gas and liquid phases. Such a configuration enhances the atomization efficiency of gas acting on water per unit area and promotes uniform atomization within the mixing chamber. As a result, the two-phase nozzle can achieve effective atomization even under relatively low air pressure, leading to reduced energy consumption. Subsequently, the water passes through the throttling rod into the mixing chamber, where it is atomized by the gas flow.

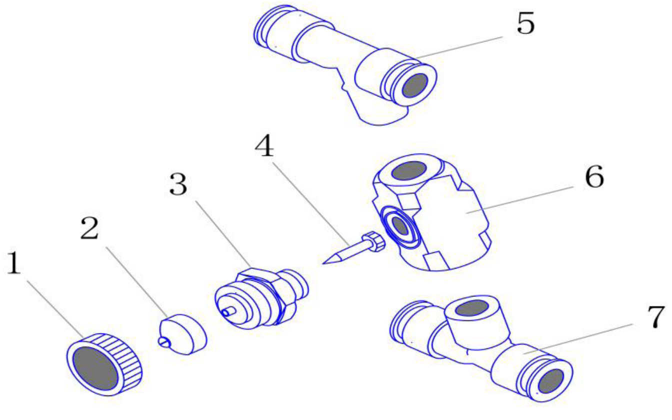

Figure 1. Assembly drawing of gas-liquid two-phase flow nozzle parts.1—Threaded sleeve, 2—Nozzle cap, 3—Small chamber, 4—Built-in throttling rod, 5—Water inlet connector, 6—Large chamber, 7—Air inlet connector.

Meanwhile, the compressed air enters a small chamber through its flow channel. The gas orifices in this chamber are designed with an offset angle in both the axial and radial directions, forming a swirl passage that induces a strong vortex flow. This swirling structure significantly increases the gas velocity, causing the airflow to move rapidly along the gas channel in a consistent clockwise or counterclockwise direction. Under a given supply pressure, the compressed air accelerates and swirls as it exits the vortex structure, directly impinging on the low-velocity liquid jet emerging from the water outlet within the gas–liquid mixing chamber. Through combined mechanisms of impact, extrusion, and shear between the gas and liquid phases, the water stream is fragmented into fine droplets.

In addition, the mixing chamber functions as a resonant cavity. The high-speed gas repeatedly interacts within the chamber, generating resonance effects that induce ultrasonic vibrations. The tensile and shear forces associated with ultrasonic resonance further refine the droplets, completing the primary atomization process. Finally, as the gas–liquid two-phase flow converges and accelerates at the protruded outlet of the spray orifice, the droplets further absorb the kinetic energy of the gas, resulting in additional size reduction and an increased spray range. This process culminates in secondary atomization at the nozzle outlet, producing a fine and well-dispersed water mist suitable for efficient dust suppression.

3. Engineering application test and analysis at Halagou Coal Mine in the Shendong Mining Area

Halagou Coal Mine is a super-large modernized mine constructed by the integration of local small-scale mines under the Shenhua Shendong Coal Group. The mine covers an area of 72.4 km², with industrial coal reserves of 995 million tons and recoverable reserves of 680 million tons. It was officially commissioned at the end of 2004, with an approved annual production capacity of 12.5 million tons and a designed service life of 52.4 years. Located in a shallow coal seam mining area, Halagou Coal Mine is characterized by stable geological structures and belongs to a low-gas mining district. The underground mining operations are highly mechanized, making the mine a representative example of the Shendong mining area.

The 22410 fully mechanized longwall face is the tenth longwall panel in the No. 4 subdistrict of the No. 22 coal seam. The face has an advanced length of 2587.9 m and a total mining area of 7.76×10^5 m², with geological reserves of 5.147 million tons. Its corresponding surface location is Haoxiahao Village. The coal seam floor elevation ranges from 1132 to 1154.7 m. Within the mining area, the coal seam thickness varies from 3.6 to 5.8 m, with an average thickness of 5.1 m. The seam exhibits a simple and stable structure, with consistent occurrence and favorable coal quality characterized by low ash content, low sulfur content, and high calorific value, indicating high suitability as thermal coal. The coal seam mineability index is 1.0, and the coefficient of variation of seam thickness is 16.1%. The seam dips toward the southwest with a gentle inclination of 1–3°, and the floor elevation of the haulage roadway is generally higher than that of the return airway, with a maximum elevation difference of 6.9 m.

Based on the dust generation characteristics of the major production processes at this longwall face and the properties of respirable coal dust, an optimization scheme for gas–liquid two-phase flow spray nozzles and their optimal layout was proposed. Respirable dust concentrations were measured at multiple key locations to evaluate the dust suppression performance of the optimized two-phase spray system under actual mining conditions.

At the coal inlet of the crusher transfer point on the 22410 fully mechanized longwall face, two rows of gas–liquid two-phase atomization devices were installed on the roof, with a spacing of 50 cm between the rows. Each row consisted of four newly developed gas–liquid two-phase dust suppression nozzles, together with corresponding air–water pipelines and protective baffles. The spacing between adjacent gas–liquid two-phase nozzles was 32 cm, as illustrated in **Figure 2**.

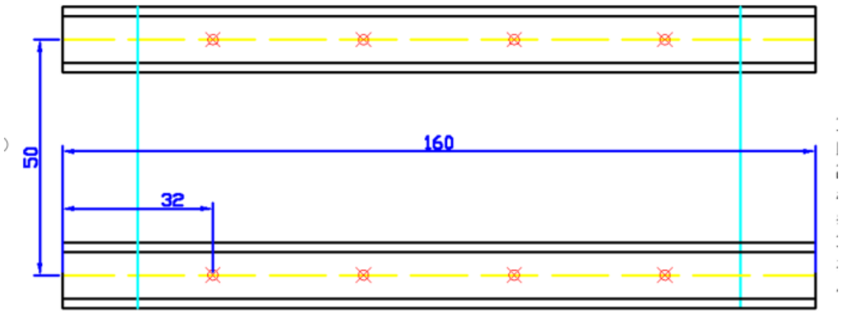

Figure 2. Temperature and humidity of 22410 fully mechanized mining face.

Similarly, at the coal outlet of the crusher transfer point on the 22410 fully mechanized longwall face, two rows of gas–liquid two-phase atomization devices were installed on the roof with an inter-row spacing of 50 cm. Each row comprised four newly designed cloud-mist dust suppression nozzles, along with air–water pipelines and protective baffles. The spacing between the cloud-mist nozzles was 27 cm. The protective baffles extended 1 cm above the nozzle outlets, providing effective mechanical protection without adversely affecting spray formation, as shown in **Figure 3**.

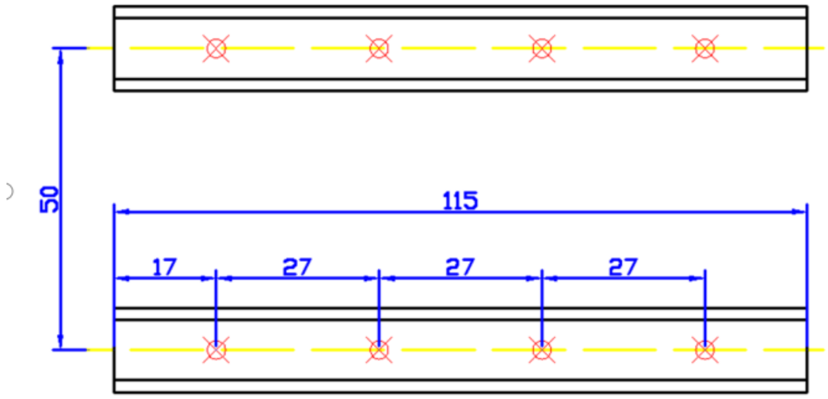

Figure 3. Temperature and humidity of 22410 fully mechanized mining face.

Multiple tests were conducted at different mining operation periods using a self-developed long-range portable dust sampling device. Continuous multi-point sampling of respirable dust in the roadway air at the crusher transfer point of the 22410 fully mechanized longwall face was carried out under three operating conditions: without any dust suppression spray, with the existing high-pressure water spray system, and with the newly developed cloud-mist (gas–liquid two-phase) dust suppression system. A comparative analysis of respirable dust concentrations at the crusher transfer point under these three conditions was then performed.

The results show that, in the absence of any dust suppression spray, the average respirable dust concentration at the crusher transfer point was 32.5 mg/m³. When the original high-pressure spray dust control system was employed, the average respirable dust concentration decreased to 14.15 mg/m³, corresponding to a respirable dust reduction efficiency of 56.46%. In contrast, when the gas–liquid two-phase spray dust suppression system was applied, the average respirable dust concentration was further reduced to 5.7 mg/m³, achieving a respirable dust reduction efficiency of 82.46%.

These results demonstrate that the optimized gas–liquid two-phase spray system at the crusher transfer point significantly enhances the capture efficiency of respirable dust compared with the conventional high-pressure spray system.

Gas–liquid two-phase spray devices were installed along the 22410 fully mechanized longwall face, with adjacent inter-shield spray units spaced at 11.9 m. Each row of inter-shield spray devices consisted of six gas–liquid two-phase nozzles, multiple air supply pipelines, water supply pipelines, and one control box. During the shearer operation, three respirable dust sampling points, denoted as A, B, and C, were arranged on the downwind side of the shearer drum at distances of 15 m, 30 m, and 45 m, respectively. The dust samplers moved synchronously with the shearer at a constant speed to ensure consistent sampling conditions.

For comparative testing, the original inter-shield high-pressure spray system and the inter-shield gas–liquid two-phase spray system were activated separately. The respirable dust concentrations in the air on the downwind side of the shearer drum were measured under both conditions, and the results are summarized in **Table 1**.

Table 1. Concentration of respirable dust at downwind side of shearer

Spray type	Respirable dust concentration at sampling point A	Respirable dust concentration at sampling point B	Respirable dust concentration at sampling point C
High-pressure spray	32.3mg/m^3	29.3mg/m^3	27.6mg/m^3
Gas–liquid two-phase spray	6.82 mg/m3	6.15mg/m^3	6.10mg/m^3

As shown in **Table 1**, compared with the dust reduction performance observed within the confined space of the crusher transfer point, the gas–liquid two-phase spray exhibits a markedly superior respirable dust capture efficiency over the high-pressure spray on the fully mechanized longwall face. After the application of the gas–liquid two-phase spray system, the respirable dust concentrations measured at 15 m, 30 m, and 45 m downwind of the shearer drum were only 21.1%, 21.0%, and 22.1% of those obtained under high-pressure spray conditions, respectively. Following the optimization of the inter-shield dust suppression system on the 22410 longwall face, the overall respirable dust concentration in the working face was substantially reduced.

Two rows of gas–liquid two-phase spray devices were installed on the roof of the advanced support section in the return airway of the 22410 fully mechanized longwall face, with a spacing of 150 cm between the rows. Each row of spray devices consisted of six gas–liquid two-phase nozzles, air–water pipelines, and one control box. The cloud-mist nozzles were fixed into clamps by bolts with a spacing of 40 cm. The cloud-mist dust suppression devices on the roof of the advanced support in the return airway were secured by welding, and the air–water pipelines and control boxes were interconnected. During installation, the air and water pipelines were arranged to closely adhere to the surface of the advanced support in the return airway.

As the working face advanced, the gas–liquid two-phase spray dust suppression devices installed in the return airway were able to move synchronously with the mining equipment. The layout of the gas–liquid two-phase spray system in the return airway is shown in Fig.4, and the corresponding spray performance is illustrated in **Figure 5**.

Figure 4. Spray arrangement of gas-liquid two-phase flow in the return air lane.

Figure 5. Spray effect of the return air lane.

Three dust sampling points, denoted as A, B, and C, were arranged at locations 3 m upwind, 5 m downwind, and 10 m downwind of the gas–liquid two-phase spray device in the return airway, respectively. During normal operation of the shearer on the fully mechanized longwall face, the gas–liquid two-phase spray dust suppression system in the return airway was activated, followed by respirable dust sampling.

The average respirable dust concentration at sampling point A was 15.7 mg/m³, while the concentrations at points B and C were 8.16 mg/m³ and 4.83 mg/m³, respectively. After passing through the optimized dust suppression system in the return airway, the respirable dust concentration decreased significantly. Relative to the concentration at point A, the dust reduction efficiencies at points B and C reached 48.0% and 69.2%, respectively.

4. Conclusion

Based on a systematic analysis of the dust generation characteristics at major emission sources on the 22410 fully mechanized longwall face of Halagou Coal Mine, as well as the physicochemical properties of respirable dust within the working face, targeted optimization strategies were developed in accordance with actual production conditions. The dust suppression systems at the crusher transfer point, inter-shield spray positions, and the return airway were comprehensively optimized by redesigning the number, spacing, and layout of spray devices. In addition, conventional high-pressure water spray systems were replaced with gas–liquid two-phase spray dust suppression devices to enhance atomization performance and dust capture efficiency.

Field validation results demonstrate that the optimized dust control system significantly improves respirable dust suppression performance across the entire longwall face. At the crusher transfer point, the respirable dust reduction efficiency increased by 26.0% compared with the original high-pressure spray system. Within the inter-shield region, respirable dust concentrations were reduced to only 21.0–22.1% of their original levels. In the return airway, the respirable dust concentration was reduced by up to 69.2%.

Overall, the proposed optimization scheme effectively achieves substantial reductions in respirable dust concentrations on the fully mechanized longwall face, thereby mitigating dust-related health risks to underground workers and improving occupational safety conditions. The results provide strong engineering evidence supporting the practical application of gas–liquid two-phase spray technology for dust control in coal mines and contribute to the advancement of safe and sustainable coal mining practices.

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Disclosure statement

The authors declare no conflict of interest.

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