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A Novel Control Technology of Hydrogen Sulfide in Fully Mechanized Excavation Face

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Abstract

Hydrogen sulfide emission affects the safety of mine production during mining of a fully mechanized excavation face. To solve this problem, on the basis of site measurement analysis of the hydrogen sulfide distribution law of the fully mechanized excavation face, a new technology is proposed with a wind curtain ventilator to seal the fully excavated section and establish a hydrogen sulfide control flow field. This technology can be used to prevent the overflow of hydrogen sulfide and elucidate closed flow theory of the wind curtain ventilator. Based on fluid mechanics theory, the potential superposition principle, and aerodynamics, a mathematical model for a closed flow theory of wind curtain ventilator in a confined space was established with No. 8116 fully mechanized excavation face of Jinniu Coal Mine in China as the background. Simulated roadway was built to test jet velocity of closed flow field, verifying the rationality of the mathematical model. Experimental results show that, the velocity of wind curtain constantly decreases with the increase in jet distance and exhibits a change trend of fast followed by slow. The theoretical wind velocity calculated with the mathematical model is consistent with the measured wind speed, and the mathematical model is accurate and reliable. When the initial velocity of the jet is 15 m/s, the effective suction range of the wind curtain fan is 4.0–4.2 m. The measured radial jet wind speed is above 2.5 m/s, which can effectively inhibit the outward escape of hydrogen sulfide. The concentration of hydrogen sulfide at the driver of the seam driving machine is reduced from 43.5 ppm to 3.0 ppm through field installation and application, and acceptable control effect of the hydrogen sulfide danger is obtained. Therefore, the obtained conclusions have greatly reference values to prevent and control hydrogen sulfide hazard in the fully mechanized excavation face.

Keywords: Fully mechanized excavation face, Hydrogen sulfide control, Wind curtain ventilator, Closed flow field, Concentration, Annular jet

1. Introduction

Coal, an important part of China’s energy structure, plays an important role in the national economic development process [1]. In the future of several decades, coal will continue to be the dominant energy for China’s industrial production and modernization [2]. However, coal mine has been a typical high-risk industry. Safe and efficient mining is a long-term and arduous task that needs to be achieved, requiring to further deepen the research on the prevention and control of harmful factors in coal mining [3-4]. The fully mechanized excavation face is one of the main production lines in coal mines with the characteristics of high production concentration, high mining intensity, and closed working space, which is an accident-prone area [5]. In recent years, the poisoning accidents caused by hydrogen sulfide gas gushing in the roadway excavation process show an increasing trend, which seriously threatens the safety of mine production [6-7]. Statistically, high-sulfur coal mines account for 36.6% of China’s national coal total [8]. With the gradual exhaustion of low-sulfur coal resources and the advancement of desulfurization technology, the exploitation of high-sulfur coal mines has become inevitable. Yet high-sulfur coal contains a large amount of hydrogen sulfide. At present, the research on the prevention and control technology of coal mine hydrogen sulfide gushing disaster has not really attracted people’s attention. In addition, the sudden gushing of hydrogen sulfide in the process of tunneling is liable to safety accidents, which have become major hidden dangers of high-sulfur coal mines. Therefore, studying the hydrogen sulfur treatment technology of the fully mechanized excavation face is greatly important to ensure the safety of mine production and improve the production efficiency.

A considerable number of mines develop excessive hydrogen sulfide due to the continuous expansion of the depth and scope of coal mining. The intensity of hydrogen sulfide gushing from mines with hydrogen sulfide hazards has increased [9]. According to incomplete statistics, more than 100 coal mines in China, have encountered incidents of hydrogen sulfide gushing and wounding [10]. A large number of hydrogen sulfide gushes out during the mining process, endangering the health of the staff, corroding the coal mine machinery and equipment, and seriously affecting the normal production of the coal mine [11]. The treatment technology of hydrogen sulfide at home and abroad mainly includes increasing the air volume of the working face,

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spraying the alkali matrix water mist, and injecting alkali liquor into the coal seam [12]. The control measures lack pertinence given the limited understanding of the amount of hydrogen sulfide in coal seam and the law of migration and distribution after gushing. Most mines only use a single method in the treatment process. Although this approach has obtained some achievements, the concentration of hydrogen sulfide gushing out in the process of digging is still below the safe value in the actual situation. The existing hydrogen sulfide treatment technology has certain limitations, and the effect is unsatisfactory. Therefore, the research on coal mine hydrogen sulfide treatment technology has become an urgent problem in China's coal mine safety production and even in the world's coal production. By forming an air curtain shield between the fully mechanized face and the workers, the spread of hydrogen sulfide to the workers' area can be controlled, thereby improving the efficiency of hydrogen sulfide treatment, that is, clean and pollution-free. Therefore, air curtain is the key to improve the effect of hydrogen sulfide purification in the fully mechanized face.

In this view, the wind curtain technology is used to treat coal mine hydrogen sulfide gushing, and a wind curtain machine is designed for the restricted working space of the fully mechanized face. Thus, a closed flow field is formed to close the roadway section and prevent hydrogen sulfide and high concentration dust from spreading to the staff position. The hydrogen sulfide management of China Jinniu Coal Mine's 8116 fully mechanized face is carried out to test the engineering application effect of the wind curtain machine to treat the hydrogen sulfide, thereby providing theoretical support for the fully mechanized face hydrogen sulfide hazard management. Therefore, preventing and controlling the hydrogen sulfide gas and coal dust gushing out from the fully mechanized coal mine face by using a clean and efficient method and guaranteeing the safe production and health of the staff have become hot research topics.

2. State of the art

Currently, scholars at home and abroad have carried out research on the treatment of hydrogen sulfide. It can be divided into active and passive prevention and control, mainly including four treatment methods, namely, physical adsorption, chemical neutralization, ventilation improvement, and foam prevention [13-14]. The first method is reducing the concentration of hydrogen sulfide by physical absorption [15]. Asaoka et al. [16] developed a granular coal ash made from fly ash of thermal power plant and blast furnace cement, and then conducted batch experiments to evaluate the removal of hydrogen sulfide by granular coal ash, showing that granular coal ash was effective in removing hydrogen sulfide under anaerobic and aerobic conditions. Satoshi et al. [17] investigated the effect of coal ash composition used for the preparation of granular coal ash on hydrogen sulfide removal performance and found that the manganese, magnesium, and calcium contents of granular coal ash were the main factors controlling the hydrogen sulfide removal rate. Pivovarova et al. [18] controlled hydrogen sulfide by ultrasonic waves and constant magnetic fields, ensuring that the content of hydrogen sulfide is reduced to less than 10 ppm. If treated with absorbent, then the content of hydrogen sulfide can even be reduced to 1 ppm. Satoshi et al. [19] developed an adsorbent for the removal of hydrogen sulfide gas and revealed its removal mechanism. A pilot scale experiment was carried out by the adsorbent to achieve high removal performance for dry and wet hydrogen sulfide gas. Chemical neutralization is used to offset hydrogen sulfide in two ways: spray and injection [20]. In the spray method, alkaline solution is prepared, and then sprayed onto the roadway to treat hydrogen sulfide. In the liquid injection method, alkaline absorption liquid is injected into the coal seam to reduce the concentration of hydrogen sulfide in the coal body. Zhang et al. [21] sprayed modified lye to treat hydrogen sulfide on site with the 2303 working face of Cuijiagou Coal Mine as the test site. The removal rate of hydrogen sulfide was 90.3% on the average, and no hydrogen sulfide overrun and secondary escape phenomenon occurred; thus, the treatment effect was remarkable. Wang et al. [22] adopted deep-hole controlled pre-splitting blast technology to increase the permeability of the coal seam. They also injected lye for soft and low permeability coal seams to improve the efficiency of the treatment of coal seam hydrogen sulfide. Zhang et al. [23] investigated the reaction of hydrogen sulfide production in coal seams by coal petrography, X-ray diffraction, and other techniques, and then proposed a high-pressure cyclic pulse alkali injection treatment technology that can effectively control high concentrations of hydrogen sulfide and prevent mine shutdowns related to hydrogen sulfide. Yuan et al. [24] governed hydrogen sulfide in a workplace by injecting alkali into a coal seam and inferred the alkali injection of the parameter relationship with conservation laws in chemistry, combining the emission of hydrogen sulfide in a coal seam with the coal mining speed. Liang et al. [25] first adopted the combination of a numerical simulation and an experiment in a scene to study the treatment of mine hydrogen sulfide according to the occurrence characteristics of hydrogen sulfide in China Tiexin Coal Mine and the alkali injection parameter relationship. Zhang et al. [26] studied the effects of different concentrations of surfactants and oxidants in sodium carbonate solution on the removal of hydrogen sulfide gas, with a single sodium carbonate alkaline solution as the basic raw material to improve the absorption efficiency of coal mine hydrogen sulfide alkaline solution. The sodium dodecyl benzene sulfonate (SDBS) and hydrogen peroxide were added to change the absorption of the alkaline solution. The ventilation improvement method is used to reduce the concentration of hydrogen sulfide by optimizing the ventilation system [27]. Wang et al. [28] improved the ventilation system of the fully mechanized working face and developed a process technology and supporting equipment for the integrated treatment of hydrogen sulfide extraction and purification in coal mines. Field applications showed that the hydrogen sulfide extraction efficiency reached 91.8%, the purification efficiency reached 93.5%, and the hydrogen sulfide hazard control effect was good. Xiao et al. [29] provided a theoretical basis for further understanding the enrichment patterns of gas and hydrogen sulfide in working faces through parameter testing, gas composition analysis, and optimization of ventilation systems. In the foam prevention method, foam is used to cover the coal body to isolate hydrogen sulfide. The foam has a large specific surface area, allowing the absorbent to capture hydrogen sulfide and improving the prevention effect [30]. Liu [31] proposed the use of foam absorbent to control the hazard of hydrogen sulfide emission from a fully mechanized excavation face, improved the generation system and arrangement form of the foam, and obtained an ideal application on-site. Deng et al. [32] analyzed the treatment effect and main problems of the existing prevention and control technology and proposed a comprehensive prevention and control technology for coal mine hydrogen sulfide based on foam absorption liquid.

The hydrogen sulfide treatment processes adopted in the above study still exhibit shortcomings. For example, the alkali injection equipment has been seriously damaged because of the strong corrosivity of alkali liquor injecting into coal seams. The limitations of alkali substratum absorption liquor spray include seriously obstructing the sight of the people on the spot and wetting clothes. In addition, the efficiency of absorbing hydrogen sulfide emission is low. The extraction efficiency of hydrogen sulfide reaches only 10% because of the poor ventilation of a coal seam and the strong adsorbability of hydrogen sulfide in coal. The current hydrogen sulfide control technique does not satisfy the requirements of the site in this research. Its construction is complex, and it has a high cost. Therefore, the regularity of the distribution of hydrogen sulfide at the driving face is investigated. Initially, a wind curtain fan is used to treat the hydrogen sulfide at the fully mechanized excavation face, and then a hydrogen sulfide scheme is designed based on a close field to confirm the relationship of the physical parameters of the wind curtain fan, effective wind speed of obstructing hydrogen sulfide, and effective suction range. A mathematical model of a wind curtain fan is established given the limited fully mechanized excavation face. Moreover, its accuracy and the effect of using a jet wind curtain machine to control the hydrogen sulfide emission are verified by an experiment in a simulated tunnel and application. This approach is expected to provide new technology and practical experience for controlling the hazard of hydrogen sulfide in a fully mechanized excavation face.

The remainder of this study is organized as follows. Section 3 introduces the distribution laws of hydrogen sulfide in a fully mechanized excavation face and hydrogen sulfide treatment technology based on closed flow field, and a mathematical model for the closed flow field of the wind curtain fan is established. In Section 4, the hydrogen sulfide treatment technology of the fully mechanized excavation face is applied in actual production to verify the accuracy of the mathematical model. Finally, the conclusions are summarized in Section 5.

3. Methodology

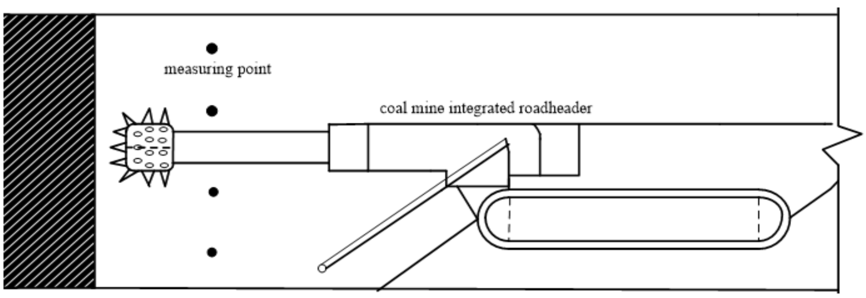
3.1 Distribution of hydrogen sulfide in fully mechanized excavation face

3.1.1 Overview of fully mechanized excavation face

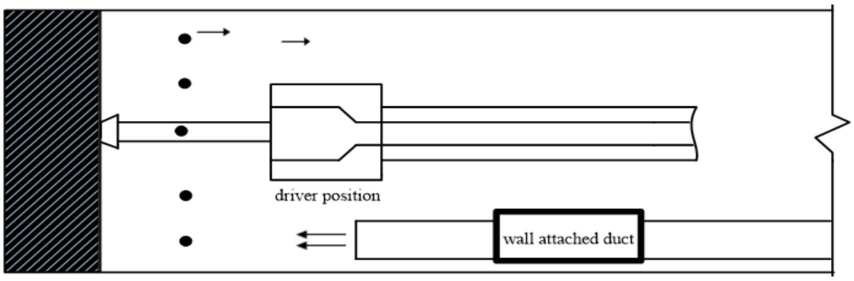
The No. 9 seam panel of Jinniu Coal Mine in China is a high-sulfur coal seam, in which the No. 8116 fully mechanized excavation face has a length of 1245 m and has a rectangular section with a size of 4.5 m×3.5 m, where bolting with wire mesh is applied. The emission of hydrogen sulfide is 6.62 L/t during the tunneling and coal cutting process. After actual gauging, the hydrogen sulfide concentration of the position of the drivers and outtake air can reach 43.5–72.5 ppm, and even more than 86 ppm in the local area, severely exceeding the standard of coal security regularities of 6.6 ppm. The increase in air supply, high-pressure spraying, purification of the water curtain, and other measures are considered in the fully mechanized excavation face to control the hydrogen sulfide pollution problem to some extent. However, the airflow remains disordered in the head-on area of the working face because of the large section of the work face and the high air supply. Some hydrogen sulfide has spread from the position of the cutting pick, causing a strong smell of rotten eggs in the position of the excavation drivers and the outtake air in the excavation roadways. Therefore, fundamentally effective techniques should be urgently considered, and the control of the work face and the treatment efficiency of the hydrogen sulfide should be enhanced.

3.1.2 Distribution of hydrogen sulfide

According to test data for the hydrogen sulfide near the fully mechanized excavation face, the emission of hydrogen sulfide was unstable in the coal cutting process. To ascertain the influence of different coal cutting positions on the emission of hydrogen sulfide, the distribution of hydrogen sulfide in the fully mechanized excavation face was detected when the heading machine cut top coal, medium coal, and bottom coal. In the section 1 m away from the coal wall of the fully mechanized excavation face, a successive layout of five measurement points was found along the horizontal direction of the roadway and four measurement points along the height of the roadway. The heading machine cut the coal for 60 s, and then the concentration of hydrogen sulfide was measured immediately. The specific layout of the measurement points is shown in Fig. 1.



(a)



(b)

Fig. 1. Layout of the hydrogen sulfide point in the fully mechanized mining face. (a) Layout of the measurement points along the height of the roadway. (b) Layout of the measurement points along the horizontal direction of the roadway

The concentration distributions of hydrogen sulfide along the height direction of the roadway in the fully mechanized excavation face are shown in Fig. 2. As shown in Fig. 2, when cutting the head coal, the concentrations of hydrogen sulfide 0.8, 1.6, 2.4, and 3.2 m away from the roadway floor were 68.3, 65.7, 48.1, and 42.8 ppm, respectively, according to the actual measurement. The coal caving and fracturing caused the hydrogen sulfide to leak in the coal cutting process, and the concentration of hydrogen sulfide near the head when cutting the top and central coal seams was higher than that when cutting the bottom coal seams. At the location 1.6 m away from the bottom of the roadway, the concentrations of hydrogen sulfide were 65.7 and 61.1 ppm for the top and central cutting coal, respectively, and increased by 2.5 to 3 times compared with the bottom coal cutting, respectively. Therefore, according to the concentration distribution of the hydrogen sulfide emission of the field detection in the fully mechanized excavation face, the governance should be strengthened mainly at the top and central emissions of the hydrogen sulfide in the cutting coal process. The distribution regularity reflects the fact that the concentration of hydrogen sulfide gradually decreases from the roadway floor to the roof in the cutting process because the high concentration of hydrogen sulfide gushing out of the coal in the passive diffusion phase does not intensively mingle with air. At the same time, hydrogen sulfide settled toward the roadway floor under the influence of air and gravity.

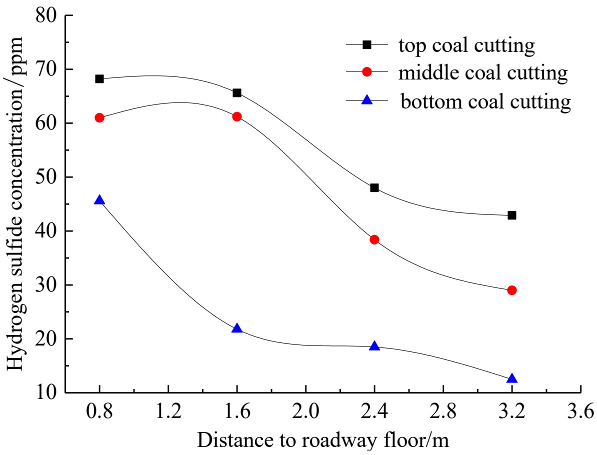


Fig. 2. Distribution of hydrogen sulfide concentration along the roadway height

To determine the concentration distribution of the hydrogen sulfide along the horizontal direction in the fully mechanized excavation face, when cutting the central coal seams, the worker's breathing zone (H=1.55 m) was regarded as the reference flat. It was measured at the pick head and 0.8 and 1.6 m from the left side and the right side, respectively. The pick of the roadheader was considered the coordinate origin. The coordinate of the inlet side was negative, and the coordinate of the return side was positive. The concentration distribution of the hydrogen sulfide in the horizontal direction is shown in Fig. 3.

As shown in Fig. 3, the concentration of hydrogen sulfide from the air input side of the fully mechanized excavation face through the pick head of the boring machine to the wind return side gradually increased. The concentrations of hydrogen sulfide reached 61.1 and 59.3 ppm at the two detection points on the wind return side 0.8 and 1.6 m away from the pick head of the boring machine, under the influence of the driving face similar to U-type ventilation. These concentrations were 3 and 5.36 times the concentration of the hydrogen sulfide at the same position on the air inlet side. Therefore, the emission of the hydrogen sulfide from the pick head of the boring machine to the wind return side of the work face must strengthen the governance.

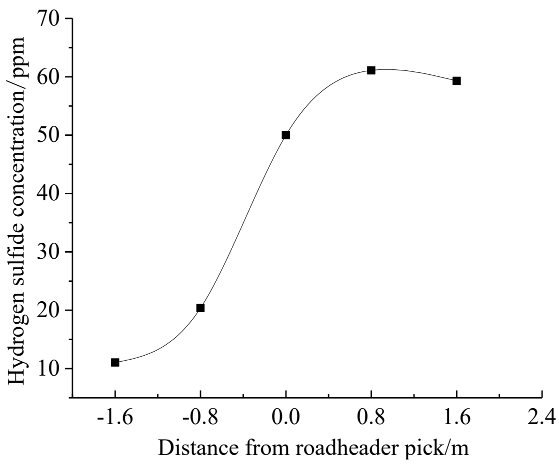
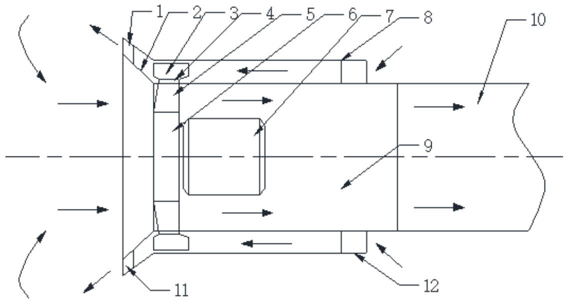


Fig. 3. Distribution of hydrogen sulfide concentration along the horizontal direction of the roadway

3.2 Technology of closed hydrogen sulfide treatment in closed flow field

The current technology for hydrogen sulfide treatment has low efficiency and high costs, and is unsatisfactory for installation and operation. Appropriate ventilation measures should be applied to control the spread of hydrogen sulfide because hydrogen sulfide only spreads with the air, ensuring a good working environment in the heading face. These measures require the establishment of an appropriate flow field of hydrogen sulfide control. A technology for hydrogen sulfide that adopts a closed flow field to close the section of a heading roadway has been proposed in this study. A hydraulic air curtain machine, as the core component of the technology of hydrogen sulfide treatment, generates a type of flow field to appropriately control the diffusion of hydrogen sulfide in a fully mechanized excavation face because of its unique interior structure to achieve the effective control of hydrogen sulfide suction. The specific device structure is shown in Fig. 4.



1-positive pressure field outlet; 2-negative pressure field inlet; 3, 4, 5-synthesis of pulley; 6-wheel hub; 7-hydraulic motor; 8-positive pressure field outlet; 9-fan outlet; 10-positive pressure field outlet; 11-positive pressure field outlet; 12-guide vane

Fig. 4. Schematic of wind curtain fume hood

Two air curtain machines are installed on the upper front right and left sides of the comprehensive tunneling machine. The hydraulic motor of the wind curtain fan is connected to the hydraulic system of the comprehensive tunneling machine, and it drives the synthetic moving wheels 3, 4, and 5 to rotate to produce two airflows. One of the two airflows is drawn in from the air inlet 8, pressurized by the air blade 3, and discharged from the air outlet 1. Thus, a conical wind curtain is formed to seal the hydrogen sulfide gushing space at the working face. Another airflow is drawn in from air inlet 2, pressurized by the air blade 4, and discharged into the hydrogen sulfide purification system through air outlet 9 and the uptake ventilator 10 of the wind curtain fan. The superposition of the external pressure flow field and the internal suction flow field is called the "closed flow field" because the speed of the curtain jet flow slowly weakens in the flow and the airflow gradually enters air inlet 2. Whether the road header is working or not, the redundant pressure of the hydraulic system reaches the power requirements of the hydraulic motor and ensures that when the road header is out of operation, jet flow is still formed to control the emission of hydrogen sulfide. When the coal is cut by the tunnel machine, hydrogen sulfide is blocked by the jet flow air curtain at the side of the tunnel end. Therefore, the gushing out hydrogen sulfide cannot gush to the personnel's position under the curtain. The wind curtain moves to the tunneling end, thus surrounding the source of hydrogen sulfide because of the influence of the wall attachment effect. Finally, the hydrogen sulfide only enters the inlet of the wind curtain fan and is discharged into the return roadway after being purified by the hydrogen sulfide fan.

3.3 Mathematical model of wind curtain fan closed flow field

To determine the space-constrained conditions of the comprehensive mechanized mining face, a mathematical model of the wind curtain fan is established to determine the relationship among the physical parameters of the wind curtain fan, the effective range of the hydrogen sulfide barrier, and the effective suction air speed. According to the analysis, the hydrogen sulfide–controlled flow field created by the wind curtain fan is caused by the superposition of three flow fields, including the convergent flow, parallel plane flow, and circular flow.

3.3.1 Mathematical parameter of convergent flow field

The complex potential of the circular convergence of the suction outlet in a spherical coordinate frame has the following formulas:

$$v_r = -\frac{Q_0}{4\pi r^2}, v_\theta = 0 \tag{1}$$

$$\varphi = -\frac{Q_0}{4\pi}\cdot\cos\theta, \phi = \frac{Q_0}{4\pi r} \tag{2}$$

In the formulas, v_r is the radial velocity of the convergent flow, in m/s; v_θ is the tangential speed of the convergent flow, in m/s; Q_0 is the convergence flow, in m^3/s; φ is the convergent flow function; ϕ is the convergence potential function.

The wind curtain fan inlet is considered the convergent flow of $(\beta/360)^2$ because the open angle of the wind curtain fan outlet is β. Its flow is $Q_1=(\beta/360)^2\times Q_0$, and substituting this expression into formulas (1) and (2) can produce formulas (3) and (4).

$$v_r = -\left(\frac{180}{\beta}\right)^2\cdot\frac{Q_1}{\pi r^2}, v_\theta = 0 \tag{3}$$

$$\phi = -\left(\frac{180}{\beta}\right)^2\cdot\frac{Q_1}{\pi}\cdot\cos\theta, \varphi = \left(\frac{180}{\beta}\right)^2\cdot\frac{Q_1}{\pi r} \tag{4}$$

The mathematical parameters of the wind curtain fan circular convergence in the plane-coordinate system are as follows:

$$u_1 = -\left(\frac{180}{\beta}\right)^2\cdot\frac{Q_1}{\pi\left(x^2+y^2\right)^{\frac{3}{2}}}\cdot x, v_1 = -\left(\frac{180}{\beta}\right)^2\cdot\frac{Q_1}{\pi\left(x^2+y^2\right)^{\frac{3}{2}}}\cdot y \tag{5}$$

$$\phi_1 = -\left(\frac{180}{\beta}\right)^2\cdot\frac{Q_1}{\pi}\cdot\frac{x}{\sqrt{x^2+y^2}}, \varphi_1 = \left(\frac{180}{\beta}\right)^2\cdot\frac{Q_1}{\pi\left(x^2+y^2\right)} \tag{6}$$

In formulas (5) and (6), u_1 is the lateral velocity of the wind curtain fan convergence, in m/s; v_1 is the longitudinal velocity of the wind curtain fan convergence, in m/s; φ_1 is the convergent flow function of the wind curtain fan; ϕ_1 is the convergence potential function of the wind curtain fan.

3.3.2 Mathematical parameter of the annular jet

After the air is emitted from the fan outlet, the air initially forms an annular jet, and the motion law of its boundary layer is similar to that from the jet boundary surface to the core position of the flow field. Although the circular jet has a certain width of the disturbance area, it is remarkably lower than the overall jet length. In addition, the flow of the boundary layer and the flow from the jet boundary surface to the core position of the flow field have relatively large velocity gradients $\partial u/\partial y$. Therefore, the overall flow process of the circular jet is clarified by the boundary surface motion equation, according to the Prandtl boundary surface motion equation, as follows:

$$\left.\begin{aligned} &u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\nu\frac{\partial^2 u}{\partial y^2}\\ &0=\frac{\partial p}{\partial y}\\ &\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \end{aligned}\right\} \tag{7}$$

In the formula, u is the lateral velocity, in m/s; v is the longitudinal velocity, in m/s; ρ is the density, in kg/m^3; ν is the kinematic viscosity, in m^2/s.

For the conditions of this study, because $\partial p/\partial x=0$ and $\nu\times\partial^2 u/\partial y^2=1/\rho\times\partial\tau/\partial y$, the previous formula (7) is further simplified as follows:

$$\left.\begin{aligned} &u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial x}=\frac{1}{\rho}\frac{\partial \tau}{\partial y}\\ &\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \end{aligned}\right\} \tag{8}$$

In the formula, τ is the turbulent stress, in N/m^2, and its formula mode is as follows:

$$\tau=\rho c^2 x^2\left|\frac{\partial u}{\partial y}\right|\frac{\partial u}{\partial y} \tag{9}$$

In the formula, c represents the experimental constants and is dimensionless.

Then, substituting formula (9) into formula (8) can produce the following:

$$\left.\begin{aligned} &u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial x}=2c^2x^2\left|\frac{\partial u}{\partial y}\right|\frac{\partial^2 u}{\partial y^2}\\ &\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \end{aligned}\right\} \tag{10}$$

Formula (10) shows the differential equation of a circular jet.

According to the characteristics of the circular jet motion, the distribution of the relative speed in the internal region of the flow field is similar, and the static pressures in different locations are the same. Using numerical and mathematical analysis based on dimensionless analysis, combined with the momentum conservation law, the mathematical mode of the circular jet can be obtained with further derivation of formula (10), as follows:

$$\varphi_2=n\sqrt{x}F(P)=2.387u_0\sqrt{B}\cdot\sqrt{x/\cos\beta+(y-r-x\tan\beta)\sin\beta}\times\left(\frac{1-\exp\left(\frac{-8.45291\cdot(y-r-x\tan\beta)}{x/\cos\beta+(y-r-x\tan\beta)\sin\beta}\right)}{8.45291}\right) \tag{11}$$

$$u_2=\frac{2.387u_0\cdot\sqrt{B}\cdot\exp\left(\frac{-8.45291\cdot(y-r-x\tan\beta)\cos\beta}{x/\cos\beta+(y-r-x\tan\beta)\sin\beta}\right)}{\sqrt{x/\cos\beta+(y-r-x\tan\beta)\sin\beta}} \tag{12}$$

$$v_2=\frac{2.387u_0\cdot\sqrt{B}}{\sqrt{x/\cos\beta+(y-r-x\tan\beta)\sin\beta}}\times\left[\frac{(y-r-x\tan\beta)\cos\beta\cdot\exp\left(\frac{-8.45291\cdot(y-r-x\tan\beta)\cos\beta}{x/\cos\beta+(y-r-x\tan\beta)\sin\beta}\right)}{x/\cos\beta+(y-r-x\tan\beta)\sin\beta}-\left(\frac{1-\exp\left(\frac{-8.45291\cdot(y-r-x\tan\beta)\cos\beta}{x/\cos\beta+(y-r-x\tan\beta)\sin\beta}\right)}{16.90582}\right)\right] \tag{13}$$

In formulas (11)–(13), φ_2 is the jet stream function; u_2 is the transverse velocity of the jet, in m/s; v_2 is the longitudinal velocity of the jet, in m/s; u_0 is the initial velocity of the fan, in m/s; B is the section width of the fan jet orifice, in m; r is the distance from the jet nozzle center to the suction nozzle center, in m.

3.3.3 Mathematical parameters of parallel plane flow

The complex potential of the parallel plane flow has the following formula in the plane-coordinate system:

$$W(Z)=(u_3\cdot x+v_3\cdot y)+i(u_3\cdot y-v_3\cdot x) \tag{14}$$

In the formula, u_3 is the horizontal wind speed between the fan and the roadway, in m^2/s; v_3 is the longitudinal wind speed between the fan and the roadway, in m^2/s; i is the virtual unit. Because u_3=Q/s, v_3=0, formula (14) can be simplified as follows:

$$W(Z)=\left(\frac{Q}{s}\right)\cdot x+i\cdot\left[\left(\frac{Q}{s}\right)\cdot y\right] \tag{15}$$

In the formula (15), Q is the air volume between the wind curtain fan and the roadway, in m^3/s; s is the longitudinal area between the fan and the roadway, in m^2.

Therefore, the mathematical mode of the parallel plane flow is derived as formula (16).

$$\varphi_3 = \left(\frac{Q}{s}\right) \cdot y \tag{16}$$

where $u_3=Q/s$, $v_3=0$, and φ_3 are the stream function of the parallel plane flow.

According to the superposition principle of the potential flow, the flow function φ of the control flow field of the hydrogen sulfide made by the wind curtain fan can be obtained under the conditions of the space-constrained fully mechanized working face.

$$\varphi = \frac{Qy}{s} + \frac{Q_1\left(\frac{180}{\beta}\right)^2}{\pi\left(x^2+y^2\right)} + \frac{2.387u_0\sqrt{B}\cdot\sqrt{x/\cos\beta + (y-r-x\tan\beta)\sin\beta}\cdot\left(1-\exp\left(\frac{-8.45291\left(y-r-x\tan\beta\right)}{x/\cos\beta + (y-r-x\tan\beta)\sin\beta}\right)\right)}{8.45291} \tag{17}$$

Formula (17) shows that the flow field is axisymmetric. According to the superposition principle of the potential flow, the convergence, circular jet, and parallel plane flow are superposed, and the transverse velocity u, longitudinal velocity v, and total velocity U for the space-constrained conditions of the full mechanized working face are obtained, as follows:

$$u = u_1 + u_2 + u_3 = \frac{Q}{s} - \frac{\left(\frac{180}{\beta}\right)^2\cdot Q_1\cdot x}{\pi\left(x^2+y^2\right)^{\frac{3}{2}}} + \frac{2.387u_0\cdot\sqrt{B}}{\sqrt{x/\cos\beta + \left(y-r-x\tan\beta\right)\sin\beta}} \times \exp\left(\frac{-8.45291\cdot\left(y-r-x\tan\beta\right)\cos\beta}{x/\cos\beta + \left(y-r-x\tan\beta\right)\sin\beta}\right) \tag{18}$$

$$v = v_1 + v_2 + v_3 = \frac{-\left(\frac{180}{\beta}\right)^2\cdot Q_1\cdot y}{\pi\left(x^2+y^2\right)^{\frac{3}{2}}} + \frac{2.387u_0\cdot\sqrt{B}}{\sqrt{x/\cos\beta + \left(y-r-x\tan\beta\right)\sin\beta}} \times\left[\frac{\left(y-r-x\tan\beta\right)\cos\beta\cdot\exp\left(\frac{-8.45291\cdot\left(y-r-x\tan\beta\right)\cos\beta}{x/\cos\beta + \left(y-r-x\tan\beta\right)\sin\beta}\right)}{x/\cos\beta + \left(y-r-x\tan\beta\right)\sin\beta} - \left(\frac{1-\exp\left(\frac{-8.45291\cdot\left(y-r-x\tan\beta\right)\cos\beta}{x/\cos\beta + \left(y-r-x\tan\beta\right)\sin\beta}\right)}{16.90582}\right)\right] \tag{19}$$

$$U = \sqrt{u^2 + v^2} \tag{20}$$

4. Results analysis and discussion

4.1 Closed flow field test and mathematical mode test

With reference to the production layout and the section size of the 8116 fully mechanized working face in China's Jinniu Coal Mine, a rectangular simulation roadway was established in the ground experimental base with a size of 60 m long, 3.5 m high, and 4.5 m wide. Moreover, the velocity attenuation experiment of the wind curtain jet was conducted. The aim of this experiment was to verify the rationality of establishing the mathematical mode of the wind curtain fan flow field and determining the change law of the fan jet velocity for the space-constrained fully mechanized working face. The top of the annular jet of the wind curtain fan was 1.6 m from the top of the built roadway and 1.2 m from the sides of the simulated roadway. The experimental equipment was mainly used, including the wind curtain fan, wind cylinder, press-in fan, hydrogen sulfide release device, and wind speed and direction meters. Two different wind curtain fans labeled A and B were designed. Their nominal air delivery was 165 m^3/min, and their nominal power was 5.5 kW. The center of the jet orifice was 0.3 m from the axis of the fan, with a driving wheel diameter of 0.5 m. The jet angle of the wind curtain fan was adjusted to 5°, the initial speed of the wind curtain was 15 m/s, and its section of the jet orifice was 18 mm wide.

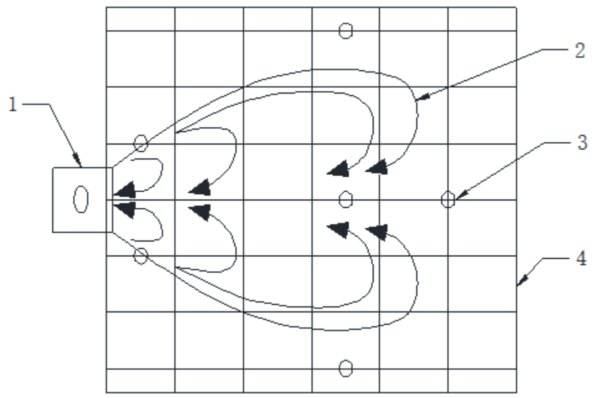
In the experiment, the wind curtain flow field was measured with the wind speed and the wind direction sensor. The measurement started from the position of the jet outlet of the fan and then measured at intervals of 0.25 m along the extension direction of the air curtain. The wind speed at each point was read in turn, and five measurements were obtained at each measuring point. Finally, the average wind speed was recorded. The streamline chart of the closed flow field was achieved according to the repeated hydrogen sulfide tracer experiment, as shown in Fig. 5. The tapered windscreen was generated by wind curtain fan 1, whose flow field 2 sealed the hydrogen sulfide 3 gushing out from the heading face. The hydrogen sulfide was mixed by the wind flow and inhaled in the fan in the closed flow field.

The physical parameters of the wind curtain fan were substituted into formulas (18)–(20), and then the formula was imported into MATLAB software. The wind speed calculated with the mathematical model formula was referred to as the theoretical wind speed. The measured windscreen velocity in the measurement position and the theoretical wind velocity are shown in Table 1. The table shows that the wind velocity of the windscreen declined gradually with an increase in the jet distance, showing the tendency change rapidly and then slowly. At the same time, the relative error in the data for each group was less than 5%. Therefore, the mathematical mode of the wind curtain fan flow field was reasonable and reliable. The experiment shows that when the initial velocity of the jet is 15 m/s, the effective suction range of the wind curtain fan is 4.0–4.2 m and the measured minimum wind speed is also over 2.5 m/s, thereby satisfying the requirement of insulating hydrogen sulfide, with acceptable treatment effect for hydrogen sulfide. The unique flow field structure of the closed flow field improves the effective suction range of the wind curtain fan, reaching more than eight times the fan suction orifice diameter. Therefore, the wind curtain fan could achieve an ideal treatment effect for hydrogen sulfide. The size of the fan is small, and it has simple operation and no spraying alkaline water curtain. Thus, the space of the digging surface and the view of the operators are unaffected, whereas the treatment cost is substantially reduced.

Table 1. Measured wind speed and theoretical wind speed in closed flow field (the center of the wind curtain fan suction port is considered the coordinate origin)

Observation posts	Abscissa x/m	Ordinate y/m	Practical wind velocity m/s	Theoretical wind velocity m/s
1	0	1D	12.80	13.10
2	0	−1D	12.69	13.10
3	0.5D	0.5D	5.71	5.87
4	0.5D	−0.5D	6.08	5.87
5	1D	0	5.75	6.13
6	1D	3D	5.66	5.48
7	1D	−3D	5.34	5.48
8	2D	3D	5.17	5.32
9	2D	1D	3.29	3.56
10	2D	−1D	3.35	3.56
11	2D	−3D	5.28	5.32
12	3D	0	2.97	3.20
13	4D	2D	2.25	2.34
14	4D	−2D	2.28	2.34
15	5D	0	2.16	2.21
16	6D	3D	1.37	1.42
17	6D	−3D	1.39	1.42
18	7D	2D	1.31	1.33
19	7D	0	1.42	1.47
20	7D	−2D	1.36	1.33
21	9D	3D	0.69	0.72
22	9D	0	1.12	1.15
23	9D	−3D	0.68	0.72
24	10D	1D	0.83	0.85
25	10D	−1D	0.82	0.85

Note: D is the diameter of the wind curtain fan suction port, 0.5 m.



1-Wind curtain fan; 2-flow field of airflow; 3-hydrogen sulfide; 4-coordinate grid (the unit length of the grid is equal to the diameter of the wind curtain fan)

Fig. 5. Streamline of closed flow field

4.2 Treatment of hydrogen sulfide in China Jinniu Coal Mine

To examine the practical effect of the wind curtain closed hydrogen sulfide treatment technology, the equipment was tested for the 8116-heading working face in China Jinniu Coal Mine. A counter-rotating pressed-in fan with a power of 30 km was used to feed air into the working face, and the actual air volume was 400 m^3/min. The wind curtain fan was 4 m from the heading end, the section width of the annular jet nozzle of the wind curtain fan was 18 mm, and the wind speed at the nozzle position was 15 m/s. The portable hydrogen sulfide detector was used to test the concentration of the hydrogen sulfide at each sample point before and after the installation of the wind curtain fan. The result is shown in Table 2.

The wind curtain fan was installed in the tunneling machine, the concentration of the hydrogen sulfide at the driver was reduced from 43.5 ppm to 3.0 ppm, and the concentration at the return air side of the fully mechanized excavation face was reduced to less than 3.7 ppm. In the middle area of the roadway 15 m from the heading end, the concentration of the hydrogen sulfide measured by the detector was 2.4 ppm, and the treatment efficiency of the hydrogen sulfide reached 95.9%, with an average of 94.2%.

Table 2. Determination of hydrogen sulfide concentration before and after addition of wind curtain fan

Test condition	Measure point area	Sample position	Hydrogen sulfide	
			Concentration/ (ppm)	Governance efficiency/%
Not taking any step	Wind inlet side	Position of drivers	43.5	-
		5 m behind the drivers	35.8	-

		10 m behind the drivers	29.0	-
	Wind return side	3 m from the roadway end	66.2	-
		5 m from the roadway end	72.5	-
	Central roadway	15 m from the roadway end	58.3	-
Governance of installing the wind curtain fan	Wind inlet side	Position of drivers	3.0	93.1
		5 m behind the drivers	2.5	93.0
		10 m behind the drivers	2.1	92.8
	Wind return side	3 m from the roadway end	3.7	94.4
		5 m from the roadway end	2.8	96.1
	Central roadway	15 m from the roadway end	2.4	95.9

According to the closed treatment technology of the windscreen, the dust hazard was also controlled in the tunneling process. The field test shows that the total dust concentration decreases from 160.6 mg/m^3 to 13.9 mg/m^3, and the respiratory dust decreased from 55.3 mg/m^3 to 5.8 mg/m^3. The average dust-settling efficiency reaches 91.3% and 89.5%. The hydrogen sulfide and the dust produced by the coal cutting of the heading machine are blocked by the windscreen on the side of the heading end, which avoids the escape of hydrogen sulfide and dust for workers in the tunneling face and evidently improves the work environment of the tunneling roadways.

5. Conclusions

A hydrogen sulfide treatment scheme based on air curtain technology is proposed to solve the problem of high concentration hydrogen sulfide gushing in the process of coal mine fully mechanized excavation. A closed flow field is formed to close the roadway section by the wind curtain fan to prevent hydrogen sulfide and high concentration dust from spreading to the staff position. A mathematical model of the wind curtain fan flow field under the condition of limited space is established. On the basis of the results of this study, the following conclusions are obtained:

1) Field measurement is used to analyze the distribution of the hydrogen sulfide in a tunneling work face, and a theory and technology for controlling hydrogen sulfide emission with a closed flow field formed by a wind curtain fan are put forward. At the same time, according to the potential flow superposition principle and aerodynamics and fluid mechanics theories, the mathematical model of the closed flow field of the wind curtain fan is constructed with the conditions of limited space.

2) With the fan jet wind speed decay experiment in the ground simulation tunnel, the jet wind speed of the wind curtain fan decreases sharply in the beginning, and the wind speed decreases slowly later. According to the comparison of the measured wind speed with the calculated wind speed of the mathematical model, the relative error in the data of every group is less than 5%, which verifies the reasonableness of the mathematical model of the fan flow field and could direct the actual project.

3) The experimental results shows that when the initial jet speed is 15 m/s, the effective suction range is 4.0–4.2 m, and the minimum velocity of the measured windscreen remains at 2.5 m/s. This finding satisfies the requirement of hydrogen sulfide isolation. According to the installation application in the field, the concentration of hydrogen sulfide at the driver position decreases from 43.5 ppm to 3.0 ppm, verifying the remarkable treatment effect of hydrogen sulfide emission.

In summary, the hydrogen sulfide treatment technology of fully mechanized excavation face based on the proposed closed flow field can effectively reduce the hydrogen sulfide concentration of the working face in the tunneling process, control it below the safety value, ensure safe production of the tunneling face and the health of the staff, and provide a theoretical basis for the prevention and control of similar problems. However, many factors affect the efficiency of hydrogen sulfide treatment in fully mechanized excavation face of coal mine, and the relationship between the parameters of air curtain fan and the effective wind speed of isolating hydrogen sulfide and effective suction range is complicated. Thus, the mathematical model of closed flow field of air curtain fan is revised by collecting a large number of measured data in the future study to improve the accuracy and application scope of the model. As a result, a considerably comprehensive theoretical support is provided for the treatment of hydrogen sulfide in the tunneling face.

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