

## Research Article

# Prevention and Control of Hydrogen Sulphide Accidents in Mining Extremely Thick Coal Seam: A Case Study in Wudong Coal Mine

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Received 28 September 2020; Revised 26 November 2020; Accepted 16 December 2020; Published 7 January 2021

Academic Editor: Qingquan Liu

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Hydrogen sulphide is a toxic gas often present in coal seams and seriously threatens the lives and health of underground workers in coal mines. In this study, we theoretically modelled hydrogen sulphide generation in extremely thick underground coal mines with the +575 level #45 coal seam of Wudong Coal Mine as an example and obtained the on-site hydrogen sulphide emission pattern and spatial distribution features by combining field measurements and computational fluid dynamics simulation. The results showed that hydrogen sulphide mainly exists in the coal porous system in an adsorbed state. Because hydrogen sulphide has a molecular weight greater than the average molecular weight of air molecules, its concentration decreases with the increase of altitude to the bottom plate. When mining the upper stratified coal stratum, it diffuses widely in the working space; while when mining the lower coal stratum, it mainly concentrates at the bottom of the working face. Based on these analyses, on-site treatments were carried out using mixtures with different concentrations of sodium carbonate and sodium bicarbonate. In addition, different combinations of catalysts as well as type A and type B wetting agents were also tested. Eventually, a neutral KXL-I absorbent was developed, and the process of preinjecting absorbent and spraying absorbent was designed. The results showed that the newly developed KXL-I absorbent has high hydrogen sulphide absorption ability and is suitable for use as an absorbent in Wudong Coal Mine; preinjecting and spraying the absorbent can effectively prevent hydrogen sulphide disasters in the +575 level #45 coal seam in Wudong Coal Mine with the optimal final concentration of 0.9% and the absorption rate of 87% at the shearer of 66.6% at the support. Overall, our study provides valuable information for the prevention and control of hydrogen sulphide disasters in coal mines.

## 1. Introduction

Hydrogen sulphide is one of the common toxic gases with corrosiveness and explosiveness in coal mines [1–4]. Poisoning by hydrogen sulphide gas has caused more than 50 accidents with human casualties in coal mines in China since 2006 (Figure 1) [5, 6]. In recent years, with the increase in coal mining mechanization and mining depth, the amount of hydrogen sulphide emission from coal mines is increasing

continuously, leading to various damages to metal equipment, facilities, and working environment of underground mining faces. In particular, due to insufficient researches on the spatial distribution of hydrogen sulphide outflow, coal mines with steeply inclined and extremely thick coal seams are often prone to the occurrence of extremely severe disasters [7, 8].

Hydrogen sulphide is slightly heavier than air with a relative density of 1.189. Therefore, it often flows upward from

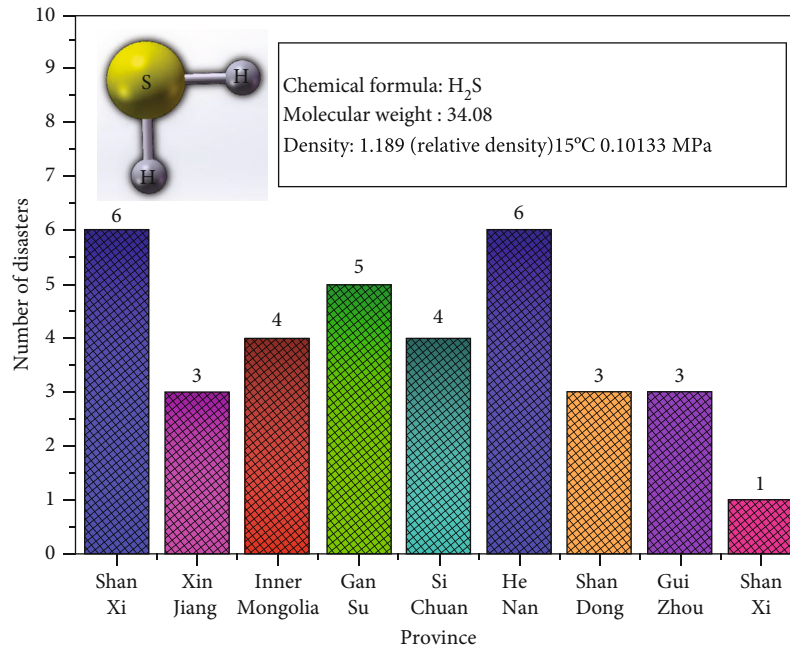


FIGURE 1: Statistics of hydrogen sulphide accidents in mines in various provinces of China since 2006. Note: on July 16, 2010, a severe hydrogen sulphide poisoning and asphyxiation accident occurred in Luanshigou Coal Mine, Xuanhan County, Sichuan Province, China, causing 6 human casualties [6–8]. In addition, hydrogen sulphide outbursts have occurred in many coal mines including Xin’an Coal Mine in Henan Province, Sangshuping and Xiayukou Coal Mines in Shanxi Province, Tingnan and Gaojiabao Coal Mines in Shaanxi Province, Wuhuliang Coal Mine, Wudong Coal Mine, Jiangou Coal Mine, Fukan No.1 well of Jiaomei Coal Mine, Chenxingyuan Coal Mine in Xinjiang Province, and Huangbaiz, Wuhushan, and Suhaitu Coal Mines of Wuhai Energy Co., Ltd. in Inner Mongolia Autonomous Region.



FIGURE 2: Location map of Wudong Coal Mine.

the ground and floats in the air of coal mining face. This special distribution in the field of coal mining face could serve as a guide for the treatment of downhole hydrogen sulphide. Many scholars have explored technologies to prevent hydrogen sulphide outflow-induced accidents in fully mechanized top coal caving faces of steeply inclined and extremely thick coal seams. At present, the most widely used methods for hydrogen sulphide treatment in coal mines are air volume regulation, acid-base neutralization, and catalytic desulphurization [9–14]. Fu et al. studied the geographical background, gas compositions, and densities as well as sulphur isotopes in

areas with abnormal hydrogen sulphide content in Zaozhuang Bayi Coal Mine and revealed the principle of underground hydrogen sulphide genesis. Li studied the characteristics of hydrogen sulphide outflow from Sukhtu and Wuhushan Coal Mines of the Inner Mongolia Wuda Mining Bureau and proposed a set of methods for systematic hydrogen sulphide treatment. Smith and Philips [15] proposed the causes of hydrogen sulphide anomalies mainly based on the data of coalbed hydrogen sulphide gas, pyrite, organic sulphur, and the sulphur isotope of sulphite. Dai [16, 17] systematically summarized a large number of related

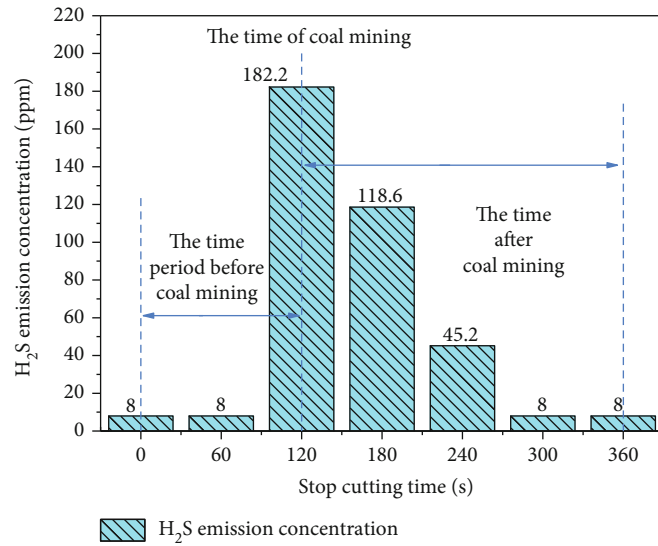


FIGURE 3: Statistical diagram of the relationship between hydrogen sulphide concentration and mining time in Wudong Coal Mine.

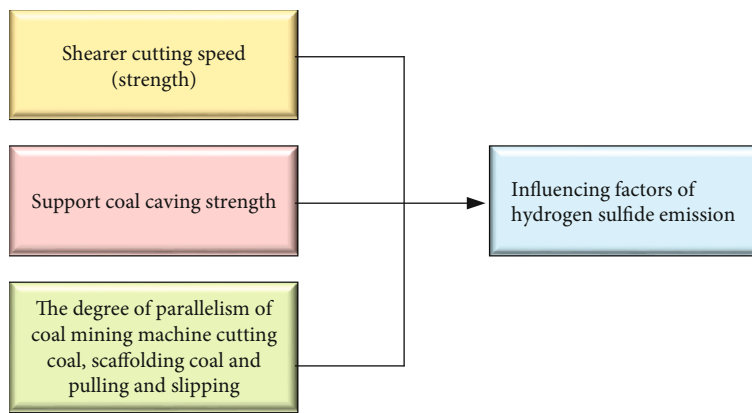


FIGURE 4: Influencing factors of hydrogen sulphide gushing.

literatures in China and abroad, proposed both the content and genesis classification schemes of hydrogen sulphide-containing natural gas reservoirs, and classified the mechanism of hydrogen sulphide genesis into 3 major categories and 5 genetic types. Chen et al. [18], based on hydrogen sulphide occurrence environment, composition characteristics, and thermal reduction reaction simulation tests, proposed the basic geological conditions required for hydrogen sulphide generation and pointed out that high hydrogen sulphide-bearing phenomena usually appear in the regions close to gas reservoirs and their beneath water body, well-sealed rock bodies and structural gas reservoirs, lower tectonic sites, and the downward dip direction of gas reservoirs. Tang et al. [19] explored the genetic relationship of the microenvironment of the Late Paleozoic coal-forming swamp in North China to sulphur in coal, divided sulphur accumulation in coal into 4 stages, and presented the relationship of pyrite formation to both sulphate and hydrogen sulphide. Taking comprehensive measures, such as ventilation enhancement, predrilling for discharge, grouting for clo-

sure, and automatic detection for treatment of hydrogen sulphide gas flowing from the tunnel wall during the construction of the Outer-circle Yuhuan Tunnel in Chongqing City [20], effectively achieved the safe passage of hydrogen sulphide-containing gas through the strata. However, the spatial shape of the coal mine underground working face is complicated, and the flow field and treatment methods are bound to be more complicated for the mining of steeply inclined and extrathick coal seams that are gradually promoted in Xinjiang, China.

In this study, to deal with the anomalies of hydrogen sulphide gas outflow from the fully mechanized mining face of steeply inclined and extremely thick coal seams in Wudong Coal Mine, we studied the spatial distribution of hydrogen sulphide in the face of the Coal Mine, proposed management measures using the finite volume method based on a completely unstructured grid and a gradient algorithm based on grid nodes and grid elements, and applied these results to realize safe and efficient production of steeply inclined and extremely thick coal seams in

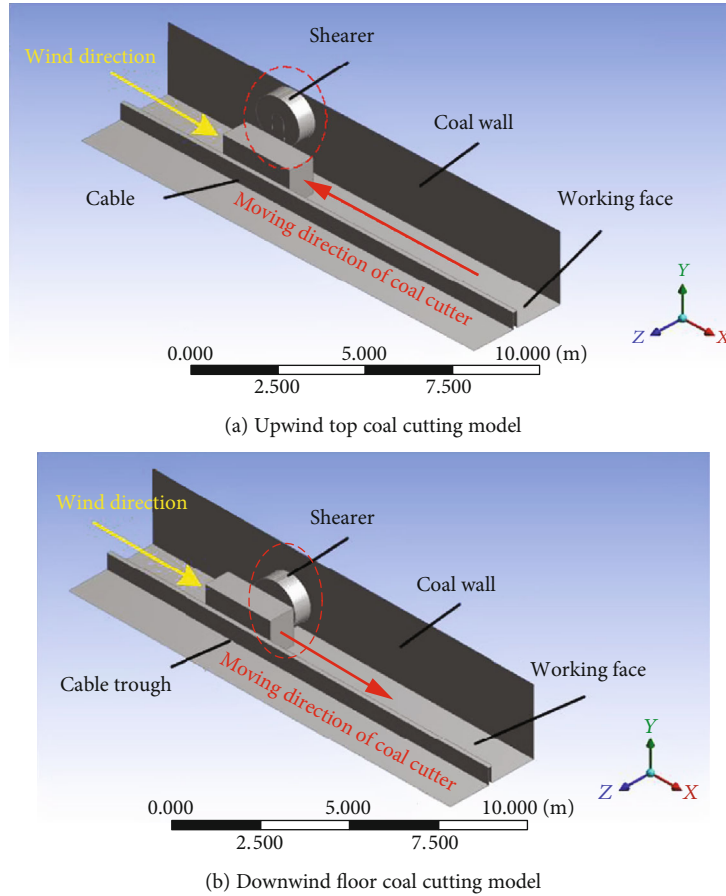


FIGURE 5: Model for coal cutting with shearers.

Wudong Coal Mine. This study is of great technical, economic, and social benefits and provides valuable experience for prevention and control of hydrogen sulphide disasters in similar coal mines.

## 2. Engineering Background

**2.1. Engineering Overview.** Wudong Coal Mine is the main mine of Shenhua Xinjiang Energy Co., Ltd. Figure 2 shows the geographical location and occurrence form of its coal seam. The coal seam in Wudong Coal Mine is steeply inclined with an underground angle to the horizon close to  $90^\circ$ . Therefore, its mining method is very different from that for an ordinary horizontal coal seam. At the present stage, the coal mine has two main mining coal seams, the #43 and #45 coal seams, both of which are extracted using the fully mechanized caving technology. During the mining of these two coal seams, excessively high concentration of hydrogen sulphide poured out from the coal seams, seriously affecting the safe and efficient mining. Especially at the +575 level, the top coal caving thickness was more than 20 m, and the amount of hydrogen sulphide outflow at the borehole exceeds 700 times of the standard of 6.6 ppm specified in *Coal Mine Safety Regulation* [21], 70 times of the standard at the coal cutting site, 140 times of the standard

at the upper corner, and 30 times of the standard at the heading and coal cutting site. Hydrogen sulphide outflow greatly impairs the safe production of the coal mine. In the recovery period of the east wing face of the #45 coal seam in the +620 level in 2010, the amount of hydrogen sulphide gas outflow suddenly increased, resulting in great casualties.

**2.2. Analysis of Hydrogen Sulphide Occurrence and Outflow Characteristics.** Hydrogen sulphide gas is mainly originated from biochemical, thermochemical, and magma processes. According to the analysis of Wudong's geological data, all recoverable coal seams in the Coal Mine belong to the humus coals formed by higher plants and have multiple layers and low metamorphic degree. Comprehensive analysis found that hydrogen sulphide gas in the coalbeds of Wudong Coal Mine mainly resulted from the forepart biochemical process of sulphur-containing organic materials and the subsequent pyrolysis of sulphate.

Hydrogen sulphide has a polarization of  $3.64 \times 10^{-30} \text{ m}^3$  [22] and higher adsorbing ability to coal than  $\text{CH}_4$ ,  $\text{CO}_2$ , and  $\text{N}_2$ . It can be clearly seen from Figure 3 that before mining, hydrogen sulphide mainly exists in adsorption form on the surface of coal and in water-soluble form. The concentration of hydrogen sulphide in the air

TABLE 1: Composition of KXL-I-, KXL-II-, and KXL-III-type absorbents.

Absorbent	Ferric chloride	Potassium iodate	Alkaline potassium ferricyanide
KXL-I	50%	25%	25%
KXL-II	25%	50%	25%
KXL-III	25%	25%	50%

in the working face area is 8 ppm. When disturbed by mining, hydrogen sulphide is converted into free state, which leads to rapid increases of its concentration in the air to 182.2 ppm. When the mining activity stopped, due to the ventilation of the coal mine, hydrogen sulphide is discharged from the working face area, resulting in the decrease of its concentration in the air to 8 ppm. In short, the concentration of hydrogen sulphide in the air will rise rapidly when the working face is normally mined, posing threats to the lives of workers.

We used a portable  $CD_4$ -type hydrogen sulphide tester to conduct both test analysis and numeric computation of hydrogen sulphide outflow from the fully mechanized west wing caving face of the +575 m level at #45 coalbed mined by the coal shearer at different mining speeds and sites (top and floor coal cutting) and with supports at different coal caving strengths. The results showed that the three main factors influencing hydrogen sulphide gas outflow are (1) the shearer mining speed (intensity), (2) supports' coal caving strength, and (3) the parallelism of coal cutting with the shearer and with the supports' coal caving and pulling/slipping<sup>[23,24]</sup>, as shown in Figure 4.

Affected by coalbed occurrence characteristics and underground mining operations, hydrogen sulphide gas during the underground mining in Wudong Mine mainly escapes from coal seams into the working area, diffuses, and gathers somewhere by ventilation airflow<sup>[25-27]</sup>, threatening underground safety production. As time goes on and mining operation continues, the threat of hydrogen sulphide gas becomes more and more serious. Therefore, it is necessary to take effective measures during the face recovery to ensure the safe and efficient production.

### 3. Numerical Simulation of the Distribution of Outflow Hydrogen Sulphide due to Mining in Steeply Inclined and Extremely Thick Coal Seam Working Face

It is clear from the above analysis that hydrogen sulphide gas desorption and outflow from coal occur only when the fractures of the coal are disturbed by coal cutting with shearers and coal caving with supports. Therefore, the excessive hydrogen sulphide gas in the working face is closely related to the underground mining production.

Many software has been used to simulate the evolution of the flow field, such as ANSYSFLUENT, FEFLOW, and FLOTHERM. Among them, ANSYSFLUENT is one of the

most commonly used in coal mining face worldwide as it has a good modelling foundation, advanced numerical methods, and powerful preprocessing functions with simulation results much closer to the actual situation on the site<sup>[28-32]</sup>. Therefore, it was selected to numerically simulate and analyze the spatial distribution and diffusion of outflow hydrogen sulphide gas with air ventilation under the disturbance of two operations: coal cutting with shearers and coal caving with supports with the west wing fully mechanized caving face of +575 level #45 coal seam of the Wudong Coal Mine as the simulation prototype.

**3.1. Numerical Model.** Establishing a coal shearer cutting coal model includes two operating conditions: upwind top coal cutting and downwind floor coal cutting.

Figure 5 shows the model of coal mining with a shearer, where (a) shows the upwind cutting of the top coal with the coal cutter on the upper part of the shearer and (b) shows the downwind cutting of the bottom coal with the coal cutter on the lower part of the shearer. Considering the spatial condition during coal cutting with shearers, relevant production conditions, and hydrogen sulphide outflow concentration at the +575 fully mechanized caving face, the model is built to simulate the process of cutting a  $20\text{ m} \times 4.4\text{ m} \times 3.5\text{ m}$  working face with its direct opposite side near the  $0.8\text{ m} \times 0.2\text{ m}$  cable trough using a  $3.4\text{ m} \times 1.2\text{ m} \times 1.7\text{ m}$  shearer at a ventilation airflow rate in the  $x$ -axis direction being 1.3 m/s. During the upwind top coal cutting, the deviation of the drum center relative to the shearer center is 1.4 m in the vertical direction ( $y$ -axis direction) and -0.3 m in the horizontal direction ( $x$ -axis direction). Hydrogen sulphide gas outflows from the coal area around the drum and the lower coal falling area. Considering the numerical calculation and field measurement of the outflow hydrogen sulphide concentration, the initial outflow hydrogen sulphide concentration is set as 510 ppm for simulation. During downwind floor coal cutting, the deviation of the drum center relative to the shearer center is 0.3 m in the vertical direction ( $y$ -axis direction) and 0.5 m in the horizontal direction ( $x$ -axis direction). Hydrogen sulphide gas outflows from the coal area around the drum, and the initial outflow hydrogen sulphide concentration is set at 340 ppm for simulation. The density of hydrogen sulphide is 1.189.

**3.2. Analysis of Simulated Outflow Distribution of Hydrogen Sulphide during Coal Cutting with a Shearer.** First, we analyzed the spatial distribution of outflow hydrogen sulphide gas induced by coal cutting with a shearer. Figure 6 shows the simulated concentrations of hydrogen sulphide gas outflow from various cross-section positions at 1 m, 4 m, 7 m, and 10 m in the downwind airflow strike of the coal mining machine by using the upwind top coal cutting models. Figure 7 shows the simulated concentrations of hydrogen sulphide gas outflow from various cross-section positions at 1 m, 4 m, 7 m, and 10 m in the downwind airflow strike of the coal mining machine by using the downwind floor coal cutting model.

From the perspective of hydrogen sulphide outflow, the numerical simulation results given in Figures 6 and 7 clearly



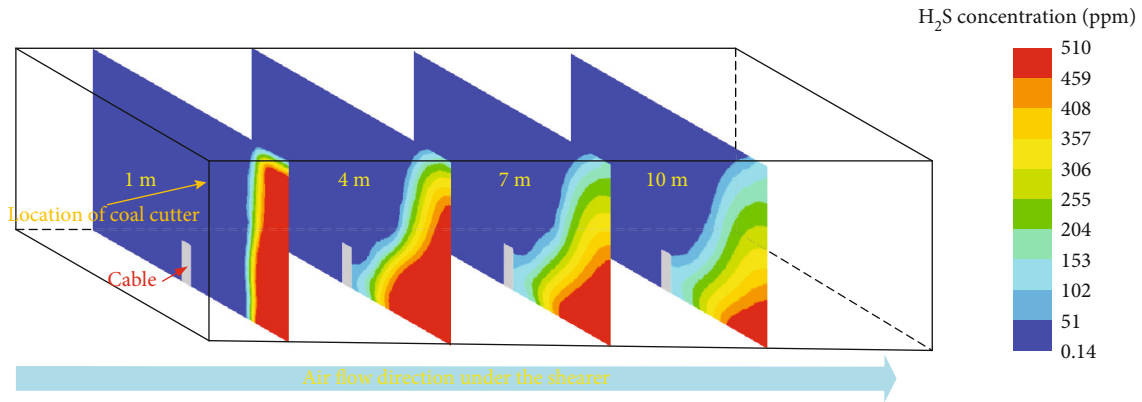


FIGURE 6: Numerical simulation diagram of the distribution pattern of hydrogen sulphide on the downwind cross-section during upwind top coal cutting.

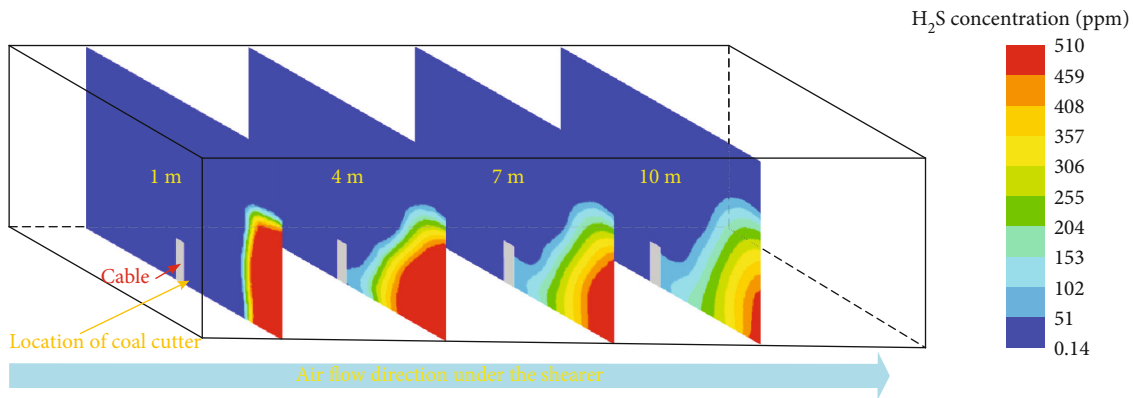


FIGURE 7: Numerical simulation diagram of the distribution of hydrogen sulphide on the downwind cross-section during the downwind floor coal cutting (0.8 m from the coal wall).

show that during the upwind top coal cutting, hydrogen sulphide outflows from the entire coal wall, filling the entire space near the coal wall, while during the downwind floor coal cutting, hydrogen sulphide outflows from the bottom rather than the top of the coal wall.

From the perspective of hydrogen sulphide migration, the numerical simulation results given in Figures 6 and 7 clearly show that because hydrogen sulphide is heavier than the air, its concentration on the same cross-section shows a gradual increase distribution trend from the top to the floor. Meanwhile, affected by wind flow disturbance at the working face, the outflow hydrogen sulphide concentration at the coal cutting sites in the downwind flow cross-section shows a gradually diffusing trend toward the sideway. At the 1 m site in the downwind direction of the shearer, hydrogen sulphide gas is not significantly accumulated and most hydrogen sulphide is concentrated at the coal wall. With the increase of the distance to the shearer, subject to both wind flow disturbance and its own sedimentation, hydrogen sulphide concentration rises significantly and shows a semiconical distribution. At the coal cutting position, a large amount of hydrogen sulphide gas surges rapidly from the coal cutting sites, reaching concentration more than 340 ppm. Affected

by wind flow disturbance and hydrogen sulphide sedimentation, hydrogen sulphide gas outflow due to coal cutting by the shearer drum gradually drops in the downwind flow direction, while its concentration in the upwind coal cutting site is relatively higher, exceeding 510 ppm.

#### 4. Hydrogen Sulphide Gas Prevention and Control Measures

Researchers in China and other countries have performed extensive studies to prevent and control serious hydrogen sulphide hazards in mining using multiple approaches such as increasing ventilation for hydrogen sulphide dilution, hydrogen sulphide drainage, spraying alkaline solution, and preinjecting alkaline absorbent for absorption. For more serious damages due to high hydrogen sulphide concentration, Wudong Coal Mine has tried to spray lime powder to artificial roadway and working face. Field application shows that such a control method is time-consuming and inefficient. In addition, lime powder cannot effectively adsorb hydrogen sulphide gas diffusing all over the entire roadway space. The poor treatment effectiveness hinders its general application. To this end, based on the physical and chemical properties

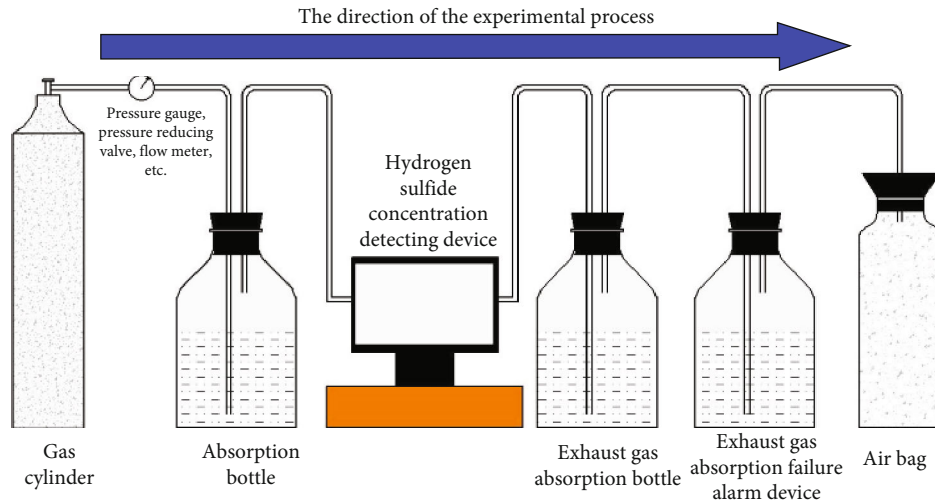


FIGURE 8: Experimental system used to test the penetration time of different types of hydrogen sulphide absorbers.

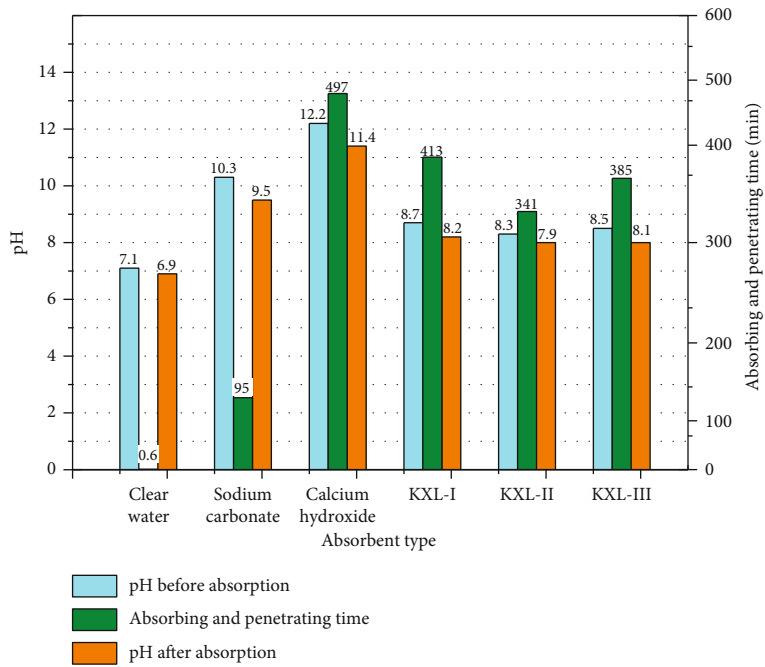


FIGURE 9: Characteristics of different types of absorbers (the penetrating value: 1 ppm).

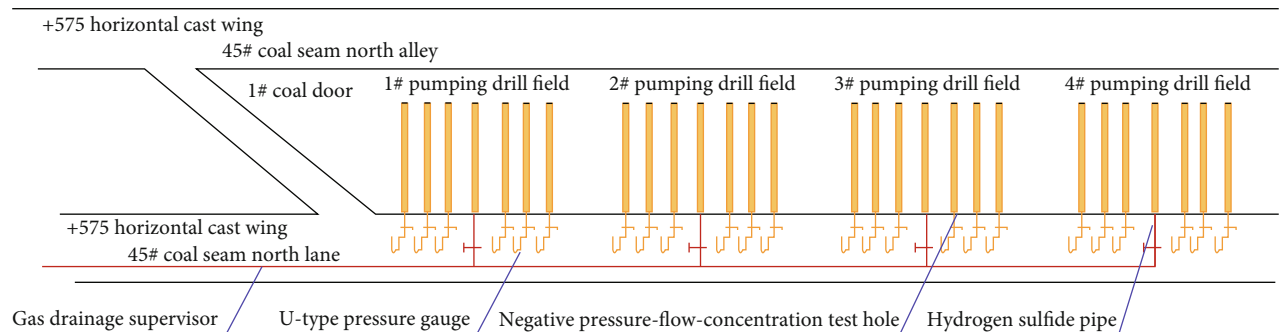


FIGURE 10: Schematic diagram of coal seam hydrogen sulphide drainage system.

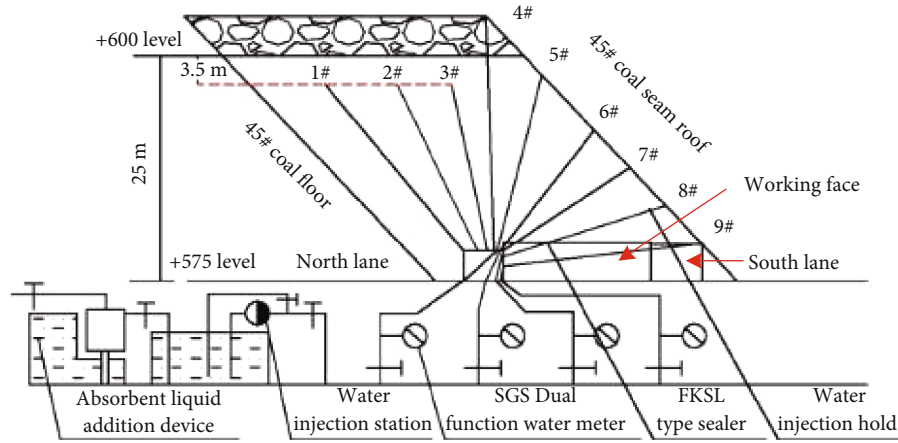


FIGURE 11: Schematic diagram of the active hydrogen sulphide prevention and control method by preinjecting absorbent liquid into the borehole in advance.

TABLE 2: The angle of each borehole for preinjecting hydrogen sulphide gas absorbent solution.

Borehole no.	1#	2#	3#	4#	5#	6#	7#	8#	9#
Angle	130°	116°	102°	91°	76°	51°	33°	18°	7°

of hydrogen sulphide gas<sup>[33–35]</sup> and the numerical simulation results of the spatial outflow characteristics of hydrogen sulphide gas, we conducted field experiments, collected and analyzed data, optimized hydrogen sulphide prevention and control scheme, and proposed a treatment system combining advanced preinjection of absorbent solution and spraying of absorbing solution to control hydrogen sulphide disasters in Wudong Coal Mine.

**4.1. Research and Preparation of Hydrogen Sulphide Absorbent.** Considering the coal and water quality as well as the field mining conditions, in the injectability study on the steeply inclined and extremely thick coal seams of Wudong Coal Mine, we selected both sodium carbonate and sodium bicarbonate as the base fluid and mixed them at different concentrations with the selected type A and B humectants and catalysts for the cross-compound tests to prepare novel and highly efficient KXL-I-, KXL-II-, and KXL-III-type hydrogen sulphide absorbents, as shown in Table 1. To examine the absorbing efficiency of these newly prepared absorbents, we compared them in the laboratory with sodium carbonate absorbent and calcium hydroxide absorbent, the two commonly used absorbents in underground mining and water cleaning. Through these tests and analyses, we obtained the highly efficient hydrogen sulphide absorbent suitable for steeply inclined and extremely thick coal seams of the Wudong Coal Mine with the aim to guarantee the highly efficient hydrogen sulphide treatment in Wudong Coal Mine.

In the laboratory, we tested the hydrogen sulphide absorption penetration time to analyze and evaluate the absorption properties of different types of hydrogen sulphide absorbents. Figure 8 shows the laboratory test system and its components. In the laboratory experiments, a certain

amount of hydrogen sulphide with purity of 99.9% was allowed to flow into the absorption bottle by adjusting the flow meter. When hydrogen sulphide concentration in the concentration detecting device reaches 1 ppm, the flow meter was adjusted to stop the outflow of hydrogen sulphide. The time of the entire process was recorded using a stopwatch. Before and after the test, pH of the absorbent solution in the absorbent bottle was measured with a pH meter.

During the laboratory tests, the flow rate and the initial hydrogen sulphide gas concentration were set at 0.2 L/min and 170 ppm, respectively; the amount of solution in the absorption bottle was kept at 150 mL; and the mixing ratios of sodium carbonate, calcium hydroxide, and KXL-I-, KXL-II-, and KXL-III-type absorbents were set to 0.2%. Figure 9 shows the test results.

Figure 9 clearly shows that the penetration times of hydrogen sulphide gas in these three newly prepared absorbents are 13, 341, and 385 min, respectively. Thus, KXL-I, KXL-II, and KXL-III absorbents all have good absorbing efficiency for hydrogen sulphide gas. At the same absorbent amount, their absorption capacity is 4.3, 3.6, and 4.1 times of that of sodium carbonate, respectively. Pure water is neutral and has a low hydrogen sulphide absorption efficiency. Sodium carbonate and calcium have the best hydrogen sulphide absorption efficiency, but they become alkaline in soluble form and could corrode equipment and negatively affect the health of workers. KXL-I, KXL-II, and KXL-III all have higher hydrogen sulphide absorption efficiency than sodium carbonate and calcium and do not have any impact on the health of workers. Among them, KXL-I is the most cost-effective. Taking all these into consideration, KXL-I was selected as the hydrogen sulphide absorbent.

**4.2. Research and Preparation of Hydrogen Sulphide Absorbent.** In view of the fact that gas drainage has been carried out for more than two years in the working face of the west wing of the +575 level #45 coal seam in Wudong Coal Mine, the dense arrangement of gas drainage holes in the coal body is not conducive to the investigation of the hydrogen sulphide drainage technology in the coal body. Therefore, 4



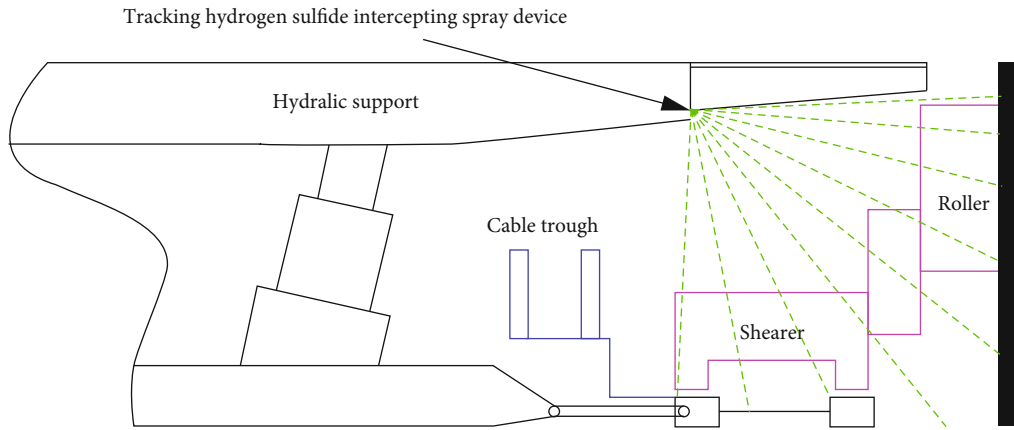


FIGURE 12: Lower airflow spray absorption system.

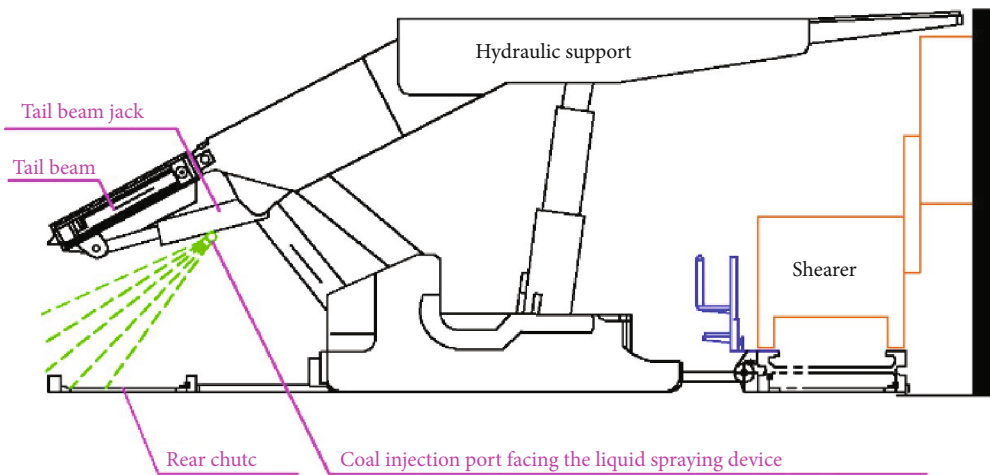


FIGURE 13: A schematic diagram of the installation of the spray absorbing device on the coal inlet.

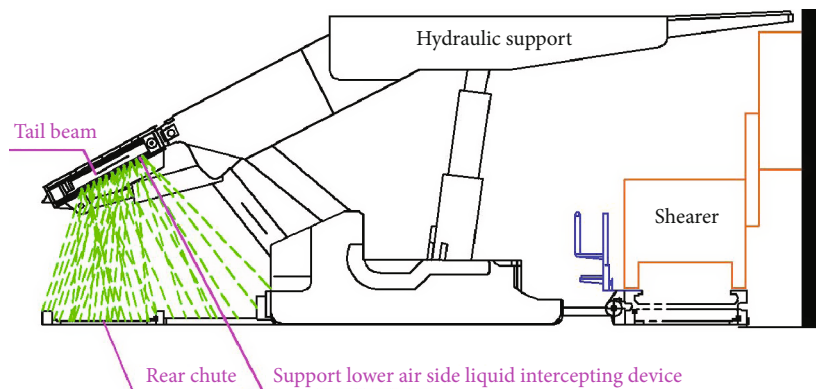
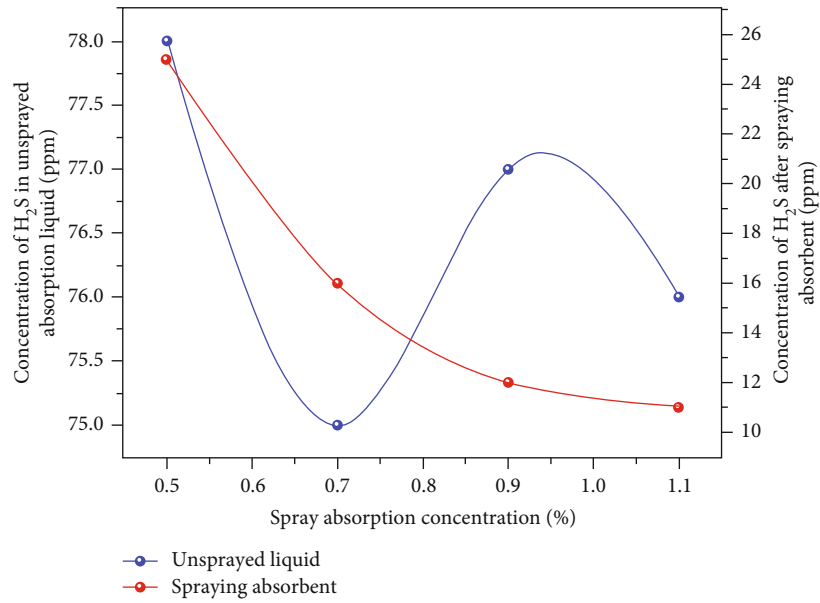


FIGURE 14: Schematic diagram of hydrogen sulphide interception spray at the coal caving port.

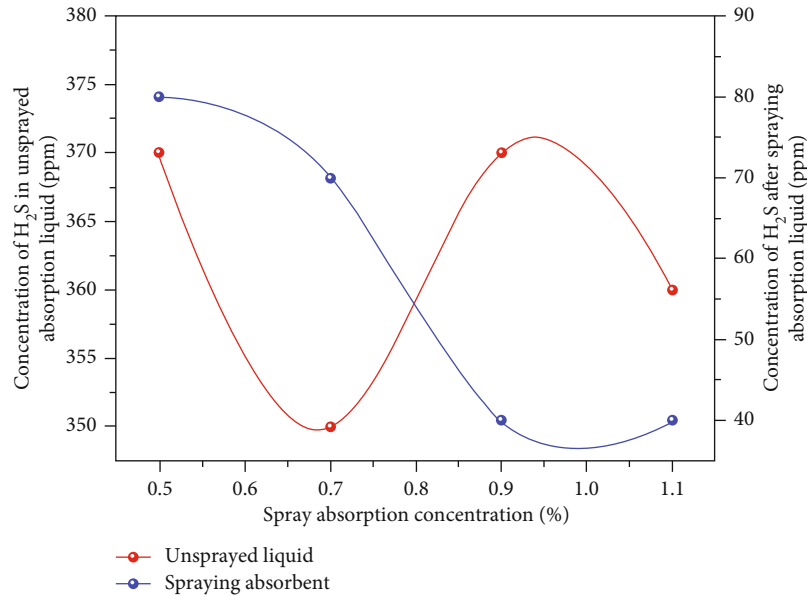
hydrogen sulphide drainage boreholes were arranged on the coal body in the coal seam drainage unaffected area between the #1 coal gate and the #2 coal gate of the fully mechanized caving face of +575 level #45 coal seam at the east wing. After sealing these boreholes with Ma Lisan, hydrogen sulphide drainage tests were conducted using the gas drainage system that has been deployed in the air intake lane to explore the

change rules of hydrogen sulphide gas drainage radius in the coal body at different negative drainage pressures (28, 26, 24, and 18 kPa). Figure 10 shows the schematic diagram of the system.

The results of drainage tests show that the influence radius of coal hydrogen sulphide drainage increases with the increase of the negative drainage pressure. When the



(a) The test point at 1.8 m from the coal wall



(b) The test point at 1.4 m from the coal wall

FIGURE 15: Relationship of hydrogen sulphide emission concentration to the concentrations of spray absorption solution.

negative drainage pressure is 28 kPa, the amount of hydrogen sulphide drainage from coal reaches a relatively stable state at about 15 days. At that time, the drainage concentration decreases from  $4600 \times 10^{-6}$  to  $300 \times 10^{-6}$ , the scalar quantity of hydrogen sulphide reduces from  $3.2 \times 10^{-4} \text{ m}^3/\text{min}$  to  $2.1 \times 10^{-5} \text{ m}^3/\text{min}$ , and the drainage influence radius is about 1~1.5 m. However, the coal's hydrogen sulphide extraction efficiency is generally in the range of 10.3% to 12.8%. Therefore, this method alone cannot solve the problem of excessive hydrogen sulphide gas.

For this reason, combined with the distribution pattern of the supporting pressure of the working face, presplit boreholes were drilled in advance on the top coal at 40 m in front

of the advancing working face, as shown in Figure 11. The angle of each borehole is shown in Table 2. According to the injectability test of the steeply inclined and extremely thick coal seams at the working face of Wudong Coal Mine, the porosity, water absorption capacity, and firmness coefficient of the coal body are 8.15%, 12.46%, and 0.8, respectively, indicating that preinjection absorption liquid technology is applicable to the coal seam.

Considering the actual situation of the site, the developed hydrogen sulphide gas absorbent solution was preinjected into the coal body, as shown in Figure 11. The borehole was sealed using the FKSL-90/16 mining borehole sealing device with the sealing depth of 4~4.8 m, the injection

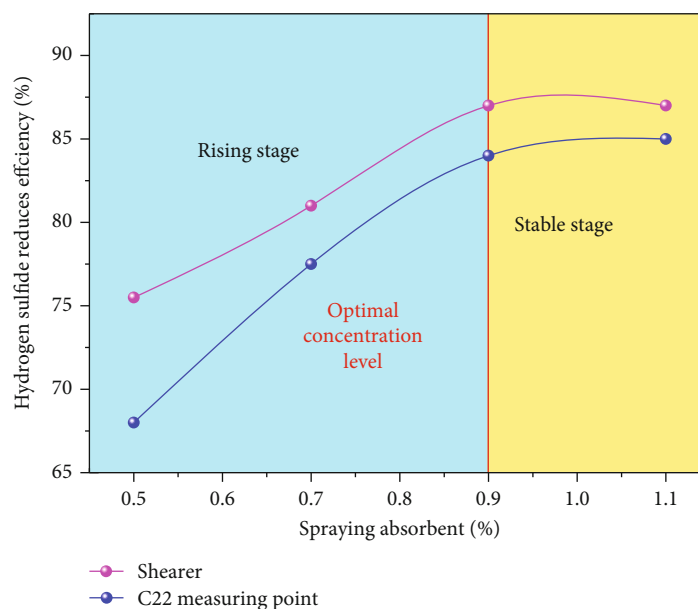


FIGURE 16: The variation of the hydrogen sulphide reduction efficiency with the concentration of the sprayed absorbent.

pressure was set at 8 MPa, the wetting agent concentration was 0.9%, and the amount of absorbing liquid for #1–9 water injection boreholes was  $\sim 56 \text{ m}^3$ .

#### 4.3. Process Technology for Treatment of Outflow Hydrogen Sulphide in Coal Mines

**4.3.1. Process Technology of Spraying Absorbents to Treat Outflow Hydrogen Sulphide due to Coal Cutting with Shearers.** Figure 12 schematically shows the absorbent spraying system and its hydrogen sulphide preventing and control principle. By installing the absorbent spraying system on the shearer, a spatial, dense hydrogen sulphide absorbing spray dome covering the roller's coal cutting area can be formed to neutralize hydrogen sulphide gas that has been initially generated due to coal cutting with the shearer. For hydrogen sulphide gas dispersed and escaped together with outward airflow, one can install on the top of the support to intercept and clear up the escaped hydrogen sulphide gas. Combined with numerically simulated results, we mainly performed the spraying with focus on the areas around the shearer and its roller so as to prevent residual hydrogen sulphide gas from amassing toward the crosswalk near the support. With comprehensive consideration of the hydrogen sulphide reduction efficiency and cost, the concentration of absorbent suitable for treatment of mining-induced hydrogen sulphide from the fully mechanized steeply inclined and extremely thick coal seam mining face is 0.9%.

**4.3.2. Process Technology of Spraying Absorbents to Treat Desorbed Hydrogen Sulphide due to Coal Caving with a Support.** Figure 13 schematically shows the technology and principle for spraying absorbents to treat released hydrogen sulphide due to support coal caving. Based on the characteristics of hydrogen sulphide gas generated due to support coal caving, we proposed the joint hydrogen sulphide manage-

ment technology by spraying absorbents toward the main hydrogen sulphide source at the support coal caving inlet and spraying absorbents toward the residual hydrogen sulphide gas in the downwind direction of the coal caving vent support. By placing the absorbent spraying device on the location right to the coal discharge vent under the two jacks of the support tail beam, an extrusive absorbent spray that can effectively cover the space of the coal discharge vent is formed to neutralize and absorb hydrogen sulphide at its initial generating site. Figure 14 schematically shows the absorbent spraying device installed on the position near the downwind side under the support tail beam and its principle of treating outward diffused and residual hydrogen sulphide gas. Using the extrusive absorbent spray to intercept and clean up residual hydrogen sulphide gas in the support rear can effectively reduce outflow hydrogen sulphide in the coal caving process, thereby minimizing the concentration of hydrogen sulphide diffused with wind to the upper corner and the return airway [36–39].

#### 4.4. Efficiency Test

**4.4.1. Characteristics of Hydrogen Sulphide Reduction Efficiency at the Site of Coal Cutting with a Shearer.** In the tests, the concentration of the spray absorbents was 0.5%, 0.7%, 0.9%, and 1.1%, respectively, the spray pressure was 8 MPa, and the spraying rate at the shearer coal cutting site and the three downwind interception sites was about 180 L/min. Figures 15 and 16 show the relationships of hydrogen sulphide outflow concentration and reduction efficiency with the absorbent concentration at the shearer site and its downwind 7 m site (the test point at 1.8 m and 1.4 m from the coal wall and floor, respectively) measured by a portable  $\text{CD}_4$  hydrogen sulphide detector.

It is clear from Figures 15 and 16 that hydrogen sulphide outflow concentration shows a gradual decrease trend with

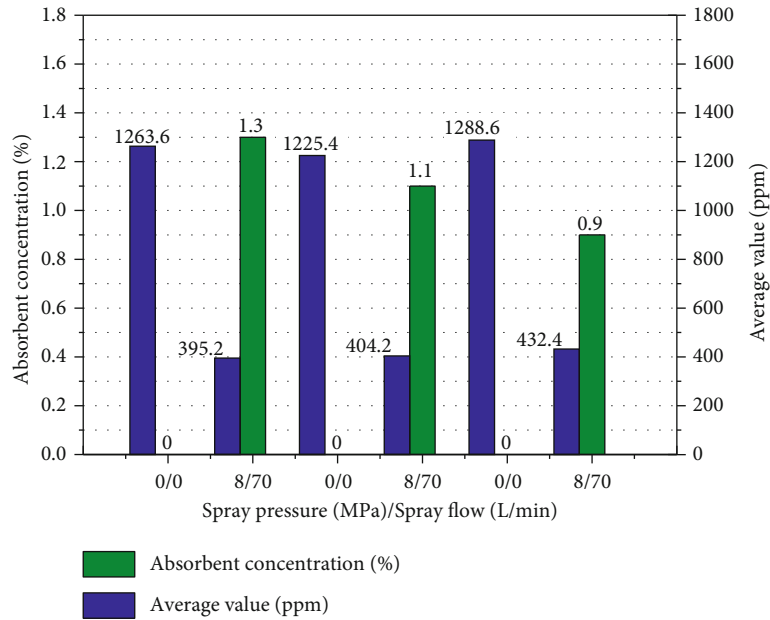


FIGURE 17: Results of testing hydrogen sulphide reduction efficiency at different absorbent concentrations. Note: hydrogen sulphide concentration is the initial  $H_2S$  concentration when spray pressure, concentration, and flow are zero.

the spray absorbent concentration increasing, whereas the hydrogen sulphide reduction efficiency shows a gradually rising trend with the spray absorbent concentration increasing. After the spray absorbent concentration increases to 0.9%, the effect of continually increasing the spray absorbent concentration to improve hydrogen sulphide reduction efficiency is less significant. Therefore, jointly considering the hydrogen sulphide reduction efficiency and cost finds that the optimal absorbent concentration used to spray and treat hydrogen sulphide outflow due to shearer coal cutting for steeply inclined and extremely thick coal seams is 0.9%.

**4.4.2. Characteristics of Hydrogen Sulphide Reduction Efficiency at the Site of Coal Cutting with a Shearer.** In order to further reduce the concentration of hydrogen sulphide rushed in the support coal caving process, we carried out experiments to examine the effect of treating hydrogen sulphide outflow at spray pressure of 8 MPa, flow rate of 70 L/min, and concentration of 0.9%, 1.1%, and 1.3%, respectively, as shown in Figure 17.

From Figure 17, it can be concluded that when the spray absorbent is 0.9%, the mean hydrogen sulphide concentration above the rear chute at 1.5 m from the downwind direction of the coal discharge vent is 432.4 ppm, which is 856.2 ppm lowering than that before spraying absorbent, showing a hydrogen sulphide reduction efficiency of 66.4%. When the spray absorbent concentration rises to 1.1%, the mean hydrogen sulphide concentration above the rear chute at 1.5 m from the downwind direction of the coal discharge vent is 404.2 ppm, lowered by 821.2 ppm with the hydrogen sulphide reduction efficiency of 67% compared with that before spraying absorbent.

When the spray absorbent concentration rises to 1.3%, the mean hydrogen sulphide concentration above the rear chute at 1.5 m from the downwind direction of the coal discharge vent is 395.2 ppm, lowered by 868.4 ppm with the hydrogen sulphide reduction efficiency of 68.7% compared with that before spraying absorbent. Under the same spray pressure and flow rate, when the spray absorbent increases to 0.9%, the effect of continually increasing the spray absorbent concentration to increase the hydrogen sulphide reduction efficiency becomes less obvious. Therefore, the absorbent concentration used to treat outflow hydrogen sulphide gas due to support coal caving in the fully mechanized steeply inclined and extremely thick coal seam mining face is about 0.9%, with the hydrogen sulphide reduction efficiency being 66.4%.

## 5. Conclusions

- (1) The downhole hydrogen sulphide gas mainly exists in adsorption and water-soluble states in the working face. When disturbed by activities such as coal mining and mobile supports, it is released into the air of the working face in the free state. Therefore, during the activities of coal mining and mobile supports, the concentration of hydrogen sulphide in the working face space increases sharply
- (2) Because hydrogen sulphide has a higher molecular weight than the average molecular weight of air molecules, its concentration gradually decreases with the increase of the distance to the floor. When mining the upper stratified stratum, hydrogen sulphide diffuses widely in the working face space while when cutting the floor coal stratum, hydrogen sulphide concentrates

mainly at the bottom of the working face. Therefore, the return air corner and tunnel are the important areas for hydrogen sulphide treatment

- (3) By mixing different concentrations of sodium carbonate and sodium bicarbonate and selecting type A and B wetting agents and catalysts for cross-compound testing, a neutral KXL-I absorbent with high absorption efficiency is developed. At its optimal concentration ratio of 0.9%, the absorption rate is as high as 87% at the shearer and 66.4% at the support, indicating that it is suitable for the treatment of hydrogen sulphide disasters in Wudong Coal Mine
- (4) Preinjecting absorption liquid to a premining coal seam and spraying absorption liquid to the source of hydrogen sulphide generation at the coal caving of the support and the residual hydrogen sulphide gas within the support effectively prevents hydrogen sulphide disasters in the working face of Wudong Coal Mine

## Data Availability

The data used to support the findings of this study are included within the article.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

## Authors' Contributions

Conceptualization was made by Xuchao Huang and Enmao Wang, methodology was handled by Xuchao Huang and Gang Wang, and data curation was prepared by Xuchao Huang and Jiuyuan Fan. All authors have read and agreed to the published version of the manuscript.

## Acknowledgments

This research was funded by the National Natural Science Foundation of China, grant number 51674158.

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