Elimination of coal and gas outburst risk of low-permeability coal seam using high-pressure water jet slotting technology: A case study in Shihuatian Coal Mine in Guizhou Province, China

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Abstract
Coal seams in China are mainly characterized by low permeability and high risk of coal and gas outburst. Therefore, the elimination of coal and gas outburst risk of low-permeability coal seam remains a hard challenge. Taking Shihuatian Coal Mine in Guizhou Province, China as an example, boreholes were slotted using high-pressure water jet to relieve the gas pressure inside the coal seam and increase the permeability of coal mass, which thus improves the gas drainage efficiency and eliminate the outburst risk. The results show that the gas drainage efficiency of the slotted boreholes significantly increases. Compared with the conventional boreholes, the average gas concentration and flow velocity improved by 1.6 and 7.5 times, respectively. Moreover, the prediction index of outburst risk is less than the critical value after high-pressure water jet slotting, which indicate that the coal and gas outburst risk has been effectively eliminated. The measured values of gas desorption index of drilling cuttings are all lower than the critical value after the application of the high-pressure water jet slotting technology. The research achievements could provide a practical reference for the effective gas disaster prevention and control in low-permeability coal seams.

KEYWORDS
ccoal and gas outburst risk, coal seam modification, gas drainage, high-pressure water jet slotting
1 | INTRODUCTION

China is a large coal producer and consumer in her medium-long-term energy strategy, coal lies at the heart of China's energy structure and will do so for many years. However, China is suffering seriously from coal and gas outburst accidents, which restricts the safe, efficient mining of coal. As coal in shallow coal seams is gradually depleted, most coal mines in China have mined deeper coal seams, where there are significantly high geo-stress, high pore pressures, high temperatures, and yet low permeability. Therefore, some dynamic disasters such as coal and gas outbursts become increasingly serious. With the increase of mining depth, the number and intensity of coal and gas outbursts occurring in heading face grows and the difficult of preventing outbursts also increases. At present, predraining gas for pressure relief in deep coal seams is the main measure to reduce the risk of gas disasters; however, owing to the permeability of coal seams being low, many drainage boreholes generally need to be drilled with a small drainage radius, resulting in delays to mining. To solve this problem, many solutions are available, including deep-hole prefracturing blasting, hydraulic flushing, water injection in coal seams, hydraulic slotting, and hydraulic fracturing. After applying deep-hole prefracturing blasting, pores with large surface areas are formed at the bottom of boreholes; however, if charges do not satisfy requirements, it is easy to trigger outbursts. Hydraulic flushing and water injection in coal seams are effective in soft coal seams under large gas pressure; however, owing to the diameter of the borehole being large, diverse defects (including hole collapse, sticking of the tool, and complex construction operations) arise during drilling.

Relying on cutting and impact capacities of high-pressure water jet, hydraulic cutting is carried out on coal seams having outburst risk with low permeability, large original geo-stress and high gas contents. In a predrilled slotted borehole, the coal masses to the sides of the borehole are cut by a high-pressure water jet. Due to the cutting and impact effects of slots induced by using the high-pressure water jets on the coal mass, flat slots of a certain width are cut from the coal mass on each side of the borehole. Moreover, some coal around the borehole is shot down and carried away by high-pressure water to form a long, narrow slot. On the one hand, the slot is equivalent to an extremely thin protective layer mined within the coal seam, which provides favorable conditions for stress release in a coal seam. On the other hand, the slots provide channels for desorption and flow of gas, thus improving the efficiency of gas drainage.

To investigate the mechanism of high-pressure water jet in breaking coal (rock) and eliminating outbursts, various engineers have carried out a series of experiments: Lin et al analyzed coal and gas outbursts in coal roadways and proposed the concept of integral pressure relief to allow further slotyping of working faces. The results showed that slotyping can be applied to prevent gas outbursts in coal seams owing to slots being able to connect boreholes to relieve gas pressure in a coal mass. Li et al decided to form a crack network through drilling and slotyping with high-pressure pulsed water jets to improve the permeability of coal seams and their gas drainage rates. Based on the mode of dynamic damage of rocks, the characteristics of dynamic damage to coal masses and the evolution of fracture fields under the effect of dynamic loads and flexible impacts were theoretically analyzed and simulated. The results showed that high-pressure water jets can fracture a coal mass under various dynamic effects (including impact, corrosion, and vibration effects), to increase the rate of fracturing of coal masses and connectivity of fractures, therefore improving their permeability. The field application results showed that the average gas drainage rate from coal seams per 100 m borehole was improved 7.8-fold compared with that using traditional methods. Si et al reported water jet slotyping technique in Montsacro Colliery, Central Asturian coal basin, Northern Spain. And he found that a large diameter slot has the advantage of deep penetration into the coal seam, which creates a large surface area and a stress relief zone. Therefore, it is recommended to aim at creating a “long and thin” rather than “short and thick” slots to maximize the stimulated zone around a borehole. However, the research on quantitative index of outburst risk before and after hydraulic slot is insufficient.

Based on the characteristics of high-pressure water jet slotyping technology, the heading face in the 11071 ventilation road, No. 7 coal seam, Shihuatan Coal Mine, Guizhou Province, China, was explored. We investigate the permeability increase and outburst prevention mechanism of high-pressure water jet slotyping technology in coal seams, expecting to provide guidance for gas prevention and control.

2 | THE EVALUATION OF THE OUTBURST RISK OF THE ORIGINAL COAL SEAM

2.1 | Basic conditions of the coal mine

Shihuatan Coal Mine is located in Zunyi County, Guizhou Province, China (Figure 1), subordinated to Chongqing Nantong Coal Industry Co., Ltd. The geological resources reserve of the mine is 3.906 \times 10^7 tons in which the designed usable reserve is 2.169 \times 10^7 tons and the recoverable reserve is 1.701 \times 10^7 tons. Moreover, the production capacity and construction capacity are separately designed to be 3 \times 10^5 tons and 4.5 \times 10^5 tons per year. Additionally, the production and service life is designed as 41 years and the remaining service life is about 35 years. In 2006, the mine is prone to coal and gas outburst in which recoverable coal seams 7 and 10 are both at risk of outburst.
2.2 | Basic conditions of the working face

The No. 7 coal seam was taken as the main mineable coal seam, with its average thickness of 1.52 m and average mining depth of 114.8 m, and the 11071 working face was the first mined in this seam. The ventilation road ran through the coal seam while the haulage road ran through the adjacent No. 9 coal seam. The 140 m long working face was mined along the inclination of the coal seam by using fully mechanised longwall mining method and was advanced along the trend of the coal seam, with a length of 892 m over a mining height of 1.5 m. The ventilation road was distributed in the No. 7 coal seam, and the haulage road was arranged in the No. 9 coal seam below. The difference in vertical distance between the upper and lower roads was about 7 m.

The experiment was carried out at the heading face in the 11071 ventilation road, and the heading face was advanced by using blasting driving. Forced ventilation was implemented using local fans and wind tubes. Owing to the coal seam having a high gas content and low permeability, it is difficult to apply advanced gas drainage. Therefore, even after taking certain steps, the gas concentration still frequently exceeded allowable limits on the heading face. According to statistics, when the heading face in the No. 11071 ventilation road was advanced to 150 m, gas concentration had exceeded the limit on over 50 occasions on the heading face. On average, the gas concentration exceeded the limit when tunneling the ventilation road, every 1.23 m; and every 3.6 m in the machinery road, wherein the maximum gas concentration reached 5.28%. Apart from gas concentrations exceeding the limit, multiple coal and gas outburst accidents induced by blasting when tunneling the ventilation road and machinery road in the 11071 working face. Although these accidents did not cause casualties, the hidden danger of outbursts always threatened safe mining. It slowed tunneling in coal roadways, and the monthly advance of the No. 11071 ventilation road was only about 40 m, which influenced the planned work over of the next face.

The experiment on high-pressure water jet slotting was carried out in the No. 111 gas drainage road at 11071 working face. The No. 111 gas drainage road (Figure 2) was a specialized drainage roadway for pre-extracting gas from 7 # and 10 # coal seams in the No. 11 mining area, which was situated in the strata between the two main mineable coal seams. The elevation was +900 m, which was 18 m away from the upper No. 7 coal seam and 2.5 m away from the lower No. 10 coal seam. The road had a semi-circular arched roof, with the net cross-sectional area of 7.86 m², which was supported by wire mesh and sprayed concrete. It can satisfy the requirements of high-pressure water jet equipment access for water supply, power supply and storage space. The strata between the gas drainage road and the No. 7 coal seam are mainly mudstone and silty mudstone, including thin limestone, in which lie the nonmineable No. 8 and 9 coal seams.

2.3 | Determination of basic parameters of coal seam

2.3.1 | Determination of the original gas pressures

The original gas pressures of the No. 7 coal seam were directly measured by drilling cross-measure boreholes. The boreholes were obliquely drilled upward from the No. 111 gas drainage road of the No. 7 coal seam through the floor and roof of the coal seam. After conducting grouting and
hole-sealing by applying cement mortar, the gas pressure in the coal seam was measured using a pressure gauge connected to the air chamber used for measuring gas pressure. The detection devices are shown in Figure 3.

According to The Direct Measuring Method of the Coal Seam Gas Pressure in Mines (AQ/T 1047-2007), when the pressure increase within 3 days was less than 0.015 MPa, it can be assumed that the gas pressure has reached an equilibrium state. To avoid the influences of environmental factors on the measured results, two cross-measure boreholes were set in the No. 111 gas drainage road in a mining area at 20 m intervals. The measured gas pressure in the boreholes is shown in Figure 4.

It can be seen from Figure 4 that the gas pressures of the two boreholes show a consistent increasing trend, taking a similar time to reach the equilibrium pressure. Eventually, the equilibrium pressures were 1.58 and 1.63 MPa (a difference of 3.07%). It indicated that the pressure measurement system for underground coal seams showed favorable stability and reliability, and therefore, the measured gas pressures were deemed accurate. The maximum measured pressure should be taken as typical case of the gas pressure in the coal seam (here the gas pressure in the mined area of the No. 7 coal seam was 1.63 MPa).

### 2.3.2 Determination of the original gas content

During construction, when measuring the gas pressure in each borehole, we needed to collect coal samples and record the time taken. After the coal samples were put into the tank, the desorption capacity of coal samples within 30 minutes was measured underground by using an air recovery method realized through water drainage. Afterward, the coal samples were sealed and degassed in the laboratory for physical desorption and then the gas loss from all coal samples in the sampling stage was deduced. Finally, according to amounts of degassing at two different stages, and the computed gas loss, the total gas content can be calculated. The DGC-type direct measuring devices for gas contents were applied in the experiment, as shown in Figure 5.

The measured gas desorption data from coal samples at different stages are listed in Table 1. According to the measured result, the sum of the gas desorption capacities was calculated: the original gas content of the No. 7 coal seam was 16.94 m³/t.

### 2.3.3 Coal seam permeability

The permeability coefficient of a coal seam is used to evaluate the complexity of gas predrainage from the coal seams, giving guidance for gas extraction and accident prevention operations in mines. The China Mining Institute Method proposed by academician Zhou et al is applied to measure the permeability coefficient of coal seams, which has been popularized and used in mines in different areas of China. Radial unstable flow theory is taken as the basis of the method. After exposing the coal seam by drilling cross-measure boreholes, instantaneous gas flows from the boreholes at different time intervals were monitored by utilizing a flow meter. According to the following formulae, the dimensionless numbers of flow and time are calculated:

\[ Y = \frac{qr}{\lambda (p_0^2 - p_1^2)}, \]  
\[ F_0 = \frac{4\lambda p_0^{1.5}}{ar^2}, \]
where \( Y \) refers to the dimensionless number characterizing the flow and \( F_0 \) denotes dimensionless time. Moreover, \( \lambda \) represents the permeability coefficient (m\(^2\)/(MPa\(^2\)·d)) of the coal seam and \( q \) refers to the gas flow (\( q = Q/2\pi r L \), m\(^3\)/(m\(^2\)·d)) per unit area of borehole wall at \( t \) time. Additionally, \( r, Q, P_0, \) and \( P_1 \) denote the radius of a borehole, gas flow (m\(^3\)/d) from a borehole at \( t \) time, the original absolute gas pressure (MPa) of the coal seam, and the gas pressure (generally, 0.1 MPa) in a borehole during gas drainage, respectively.

Moreover, \( t, \alpha, \) and \( x \) refer to the time interval (d) from the onset of gas drainage to \( q \) when measuring the gas flow, and the gas content coefficient in the coal seam and gas content (m\(^3\)) in the coal seam, respectively.

The relationship between the dimensionless numbers of flow and time can be expressed as follows:

\[
\begin{align*}
Y &= a F_0^b \\
Y &= A/\lambda.
\end{align*}
\]  

Due to the complexity of the relationship, the values of index \( a \) and exponent \( b \) vary with \( F_0 \). According to the borehole flow method, the specific values of \( a \) and \( b \) and corresponding permeability coefficients are calculated as follows (Table 2).

Where \( A = \frac{4r}{(r_0^2 - r_0^2)} \) and \( B = \frac{4r_0^{1.5}}{ar^2} \). During calculation, the corresponding \( \lambda \) value is selected at random, then, the value of \( \lambda \) is substituted into \( F_0 = B \lambda \) to verify whether, or not. \( F_0 \) is in the range of primarily selected formulaic values. If it is, the formula is correctly selected; otherwise, it is necessary to repeat these steps. The change in instantaneous gas flow from the boreholes in the No. 7 coal seam measured on site is displayed in Figure 6. By substituting the drilling parameters for uncovering coal and data on instantaneous gas flow into Formula (9), the permeability coefficient (\( \lambda \)) of the coal seam was found to be 0.004 m\(^2\)/(MPa\(^2\)·d).

### 2.3.4 Coal adsorption constants

The adsorption constants (\( a \) and \( b \)) of coal characterize the adsorption capacities of coal particles for gas and are measured based on Langmuir isothermal adsorption theory.\(^{37}\) The high-pressure methane adsorption isotherms were measured according to the MT/T 752-1997 Standard, using dynamic test apparatus for gas adsorption- and desorption-induced deformation of coal seams (Figure 7).\(^{38}\)

Isothermal adsorption tests were separately carried out on two coal samples to obtain their adsorption curves (Figure 8). By using the least squares method, the pressures for adsorption equilibrium and adsorption capacities were fitted to thus attain the adsorption constants of coal samples for gas, as follows: \( a_1 = 29.3920 \text{ cm}^3 \cdot \text{g}^{-1} \), \( b_1 = 1.5057 \text{ MPa}^{-1} \), \( a_2 = 26.5322 \text{ cm}^3 \cdot \text{g}^{-1} \), and \( b_2 = 1.3024 \text{ MPa}^{-1} \). According to the aforementioned data, it can be seen that the gas content in
the coal samples was high, conforming to the measured gas content in the coal seam on site.

2.4 Evaluation of outburst risk at the heading face

Key parameters of the No. 7 coal seam are summarized in Table 3. Moreover, according to previous research,39,40 the single critical indices for predicting outburst risk of coal seams were measured on site (Table 4).

It can be seen from Tables 2 and 3 that the No. 7 coal seam in Shihuatian Coal Mine showed various characteristics including low permeability, high gas pressure and gas content, large initial velocity of gas emissions, fractured coal masses, and thus a high outburst risk. Therefore, this coal seam has a high risk of coal outburst. In these geological conditions, applying conventional borehole predrainage cannot reduce the gas content in the coal seam and eliminate the outburst risk; therefore, it is planned to increase the permeability and eliminate the outburst risk by using high-pressure water jet slotting technology.

### TABLE 2 Calculation formula table of coal seam permeability coefficient

| $F_0$  | Formula |
|--------|---------|
| $10^{-2}$~$1$ | $\lambda = A^{1.61} B^{1/n}$ |
| $1$~$10$   | $\lambda = A^{1.39} B^{1/n}$ |
| $10^{-1}$~$10^{-2}$ | $\lambda = 1.4 A^{1.25} B^{1/n}$ |
| $10^{2}$~$10^{3}$ | $\lambda = 1.83 A^{1.14} B^{1/n}$ |
| $10^{3}$~$10^{5}$ | $\lambda = 2.1 A^{1.11} B^{1/n}$ |
| $10^{5}$~$10^{7}$ | $\lambda = 3.14 A^{1.07} B^{1/n}$ |

### FIGURE 6 Change in instantaneous gas flow in a borehole

### FIGURE 7 Dynamic test apparatus for gas adsorption- and desorption-induced deformation of coal seams

### FIGURE 8 The isothermal adsorption curves of coal samples for gas

### 3 THE REVELATION OF THE ELIMINATION PROPERTY OF THE OUTBURST RISK OF THE ORIGINAL COAL SEAM USING THE WATER JET SLOTTING TECHNIQUE

#### 3.1 Experimental equipment

The BZW75/50 high-pressure water jet equipment was used to increase permeability and eliminate outbursts. It includes a high-pressure pump station, a high-pressure spinning cutting head, a high-pressure hard hose, a pressurized drill pipe for water delivery, and a propeller, as shown in Figure 9.
The rated power, voltage, and flow of the high-pressure water pump in the system are 75 kW, 660 V, and 75 L/min, respectively, and the rated pressure during slotting is 50 MPa. During slotting, the nozzle automatically spun and cut under the driving effect of the high-pressure water and the spinning velocity was controlled by the water pressure. Moreover, the high-pressure drill pipe for water delivery was kept still. To maximize the depth of slotted boreholes, cutting was carried out using pure water without abrasives, which also avoided wear on the equipment. When no coal cinders were found in the water draining from the borehole, the slotting process was completed. Owing to the small thicknesses of the targeted coal seam, slotting was carried out only once per coal seam.

### 3.2 Procedures of hydraulic slotting and layout of the slotted boreholes

During testing, oblique, upward, strip-shaped boreholes were drilled from the No. 111 gas drainage road to pass through the coal seam in front of the heading end of the 11071 ventilation road. Afterward, by using a specialized nozzle for high-pressure hydraulic slotting, the coal masses were subjected to rotary cutting at fixed points within a section of the boreholes by employing high-pressure water jets. The cut coal cinders flowed out with the water. The slot cut caused heterogeneous deformation and failure of coal masses under formation pressure, providing a flow channel for gas.

The coal masses in front of the 11071 working face heading end were subjected to rotary slotting by high-pressure water jet and boreholes for hydraulic slotting were distributed in parallel at 3 m intervals. Three boreholes were distributed in each group and the borehole parameters of the first group are listed in Table 5. During field construction, the drilling was conducted by applying a conventional drill bit at first and then drilling was stopped after exposing the No. 7 coal seam and then drilling to a depth of 0.5 m into the roof. After the drill pipe was pulled out, the coal masses were cut by applying the BZW75/50 high-pressure water jet slotting equipment. In the experiment, the 7 #, 8 #, and 9 # coal seams were

### TABLE 3 Key parameters related to gas in the No. 7 coal seam

| Item                        | Unit          | Measured value |
|-----------------------------|---------------|----------------|
| Gas content                 | M³/t          | 16.9335        |
| Gas pressure                | MPa           | 1.63           |
| Permeability coefficient    | m²/(MPa²·d)   | 0.004          |
| Initial velocity of gas     | mm Hg         | 25–27          |
| Protodyakovon's coefficient | —             | 0.3–0.5        |
| Failure type                | —             | IV             |
| Adsorption constant $a$     | cm³/g         | 29.3920        |
| Adsorption constant $b$     | MPa           | 1.5057         |

*Note: Failure type IV, powdered coal.*

### TABLE 4 Single critical indices for predicting outburst risk and their measured values

| Values                      | Failure type | Initial velocity of gas emission/mm Hg | Protodyakovon’s coefficient | Gas pressure of the coal seam/MPa |
|-----------------------------|--------------|---------------------------------------|-----------------------------|----------------------------------|
| Critical value              | III, IV, V   | 10                                    | 0.5                         | 0.74                             |
| Measured value              | IV           | 25–27                                 | 0.3–0.5                     | 1.63                             |

*Note: Failure type III, strongly destructed coal; Failure type IV, powdered coal; Failure type V, pulverized coal.*

![FIGURE 9 Equipment used for hydraulic slotting](image-url)
successively slotted and the experiment was stopped when no coal cinders were found in return water flows. Afterward, a tube for gas drainage was buried in each borehole and the boreholes were sealed by grouting, which was also connected to the central mine drainage system.

3.3 Changes in gas flows and flow velocities

Figure 10 shows the changes in the amount of gas in slotted and conventional boreholes. As shown in the figure, the gas quantity in the borehole after slotting was up to 61.3 L/min, which was improved by 6.7 times compared with that (9.2 L/min) in conventional boreholes. The amount of gas in slotted boreholes gradually decreased with time and was sustained at 10 L/min for 6 days, higher than that in conventional boreholes. According to measured result obtained by using an orifice plate flowmeter, 8 days before gas drainage, the gas emissions from the slotted boreholes were 5.6 times greater than that from a conventional borehole. After gas drainage had been conducted for 17 days, the total gas drainage from a group of boreholes without being subjected to high-pressure water jet slotting was 649 m³. However, with the same borehole size and negative pressure for gas drainage, the total gas drainage from slotted boreholes reached 2581 m³, which was 4.5 times that from conventional boreholes.

Figure 11 shows the changes in velocities of gas emission from slotted and conventional boreholes. After applying hydraulic slotting, the velocity of gas emissions from the boreholes was significantly improved and the maximum initial velocity of gas emission per 100 m length was 7.5 times that of conventional cross-measure boreholes used for gas predrainage. Moreover, in terms of average gas drainage velocity, the former is 4 times that of the latter. Additionally, the velocities of gas emissions from slotted and conventional boreholes both decreased. According to the data in the above table, the fitted curves of velocities of gas emission can be separately expressed as follows:

\[ q_{\text{slotted}} = 636.5e^{-0.1273t} \]  \hspace{1cm} (4)

\[ q_{\text{conventional}} = 182.7e^{-0.111t} \]  \hspace{1cm} (5)

According to Formulae (1) and (2), it can be seen that the attenuation coefficients of gas emission from slotted, and conventional, boreholes were 0.1273 and 0.111, respectively, with an insignificant difference therein. This was determined by the low permeability coefficient of the coal seam. After slotting, coal masses were allowed to expand; in spite of this, fractures developed slowly under geo-stress and adjacent
slots were not connected. As a result, only some of the gas in coal masses around each individual slotted borehole was emitted. However, sufficient pressure relief conditions for gas emission had not been satisfied in deeper coal masses, and therefore, the gas desorption rate and flow velocity were still restricted.

### 3.4 Changes in gas concentration

Gas concentration in boreholes is an important index used to evaluate the effect of gas drainage. To compare the effects of gas drainage from conventional and slotted boreholes, Figure 12 shows the changes in gas concentrations in the two types of boreholes. As shown in the figure, the gas concentration in the two types both rapidly attenuated, while the gas concentration in slotted boreholes was much higher than that in conventional boreholes. The mean gas concentration in slotted boreholes was 4.6%, which was 1.6 times that (2.8%) in conventional boreholes.

### 3.5 Changes in the gas desorption index of drilling cuttings

Drilling cuttings gas desorption index can effectively evaluate the outburst risk of coal seam. After gas drainage was conducted for 17 days, the index for gas desorption of drilling cuttings at the observed boreholes in coal masses in front of the heading end of ventilation road in the 11071 working face was measured (Table 6).

According to the measured result of the gas desorption drill cuttings index, the values of $\Delta h_2$ were all lower than the critical value, with a mean of 180 Pa. The measured quantities of drill cuttings were also all lower than the critical value, with means of 4.54 kg/m and 3.17 L/m, respectively. Therefore, it can be judged that the outburst risk in local areas was eliminated after applying high-pressure water jet slotting technology to coal masses in front of a heading face and further conducting gas drainage for 17 days under a negative pressure of 25 kPa. Through trial tunneling, the gas concentrations exceeding allowable limits were controlled after blasting. Moreover, the gas concentration of the working face decreased and no strata behaviors (such as coal and gas outburst) occurred thereafter.

Overall, the high-pressure water jet slotting technology for increasing permeability effectively improved the amount of gas drainage, accelerated the tunneling velocity of the working face, and eliminated coal and gas outburst risk.

### 4 CONCLUSIONS

As an efficient technology for rock breaking, high-pressure water jetting is widely used for extracting oil gas and natural gas. Extracting gas in mines with outburst risk through borehole drilling is an effective technological measure for preventing coal and gas outbursts; however, for coal seams with a low permeability, poor results arose from drilling boreholes for gas predrainage. If high-pressure water jet technology is used to slot coal masses in boreholes in advance, the free surface area is increased and local stresses are eliminated, thus releasing the stress on coal masses. Therefore, the purpose of efficiently extracting gas is realized to thus eliminate the hidden danger of coal and gas outbursts.

Based on geological conditions and gas distribution in Shihuatian Coal Mine, a hydraulic slotting test was carried out in the No. 111 gas drainage road. In the first 8 days of gas drainage after slotting, the amount of gas flowing from the boreholes slotted by high-pressure water jets was 5.6 times that from conventional boreholes. After 17 days of gas drainage, the amount of gas emitted from a group of conventional boreholes not subjected to high-pressure water jet slotting was 649 m³. In contrast, under conditions with the same borehole diameter and negative pressure for gas drainage, the total amount of gas emitted from slotted boreholes reached

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**TABLE 6** Outburst risk by using the gas desorption drill cuttings index

| Gas desorption index $\Delta h_2$ of drill cuttings (Pa) | Quantity of drill cuttings (kg/m) | (L/m) |
|--------------------------------------------------------|-----------------------------------|-------|
| s-1#                                                   | 160                               | 4.48  | 3.1  |
| s-2#                                                   | 110                               | 4.53  | 3.2  |
| s-3#                                                   | 170                               | 4.60  | 3.2  |
| Critical value                                         | 200                               | 6     | 5.4  |

**FIGURE 12** Comparison of velocities of gas emission from slotted and conventional boreholes
2581 m³, which was 4.5 times that from conventional boreholes. Additionally, the average gas concentration around slotted boreholes was 4.6%, which was 1.6 times that of conventional boreholes (2.8%). High-pressure water jet slotting can significantly improve gas drainage.

By analyzing the indices for gas desorption in drill cuttings after slotting, it can be seen that the values of Δh₂ were all lower than the critical value, with a mean of 180 Pa. The measured amounts of drill cuttings were all less than the critical value, with means of 4.54 kg/m and 3.17 L/m, respectively. Therefore, the outburst risk of local zones was eliminated after implementing high-pressure water jet slotting in coal masses in front of the heading face after allowing gas drainage for 17 days under a negative pressure of 25 kPa. After trial tunneling, the problem of gas concentrations exceeding tolerable limits due to blasting was controlled and gas concentrations at the working face were significantly reduced. Moreover, no strata behaviors (such as coal and gas outburst) occurred.

Therefore, high-pressure water jet slotting for increasing permeability can effectively improve the amount of gas drainage from a coal seam and eliminate coal and gas outburst risk. The study offers guidance to those conducting gas drainage operations and provides a reference for those implementing gas prevention works in similar conditions.

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