A Method of Quick and Safe Coal Uncovering by Hydraulic Fracturing in a Multibranch Radial Hole with a Coalbed Methane Well

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ABSTRACT: Coal and gas outburst accidents occur most frequently during coal uncovering operation, and uncovering-induced outburst accidents have caused great economic losses and casualties. In order to quickly and safely uncover the outburst coal seam at the air intake shaft in panel 2, Zhaozhuang Coal Mine has come up with the technology of multibranch radial borehole hydraulic fracturing (MRBHF) coal uncovering technology in the surface coalbed methane (CBM) well. By conducting fracturing of constructed radial boreholes in the CBM well, the technology increases fractures, enhancing coal permeability and raising gas drainage volume in the uncovering area. It brings the following three major benefits: (1) uncovering coal efficiently, rapidly, and safely; (2) greatly reducing engineering quantity, coal uncovering period, and construction cost, i.e., significantly improving the economic benefits; and (3) efficiently reusing the CBM well. Compared with conventional uncovering measures, the proposed technology shortens the uncovering period by 118 d, enhances the coal seam permeability by 3.55 times, raises the gas drainage rate by 22%, increases the gas drainage volume by 1.93 times, and reduces the engineering volume of drilling by 12,000 m. The safe, rapid, economical, and applicable technology provides scientific guidance and reference for domestic and foreign shaft coal uncovering engineering and possesses important economic and social values and application prospect for safe and efficient production of coal mines.

INTRODUCTION

Coal and gas outburst is an extremely complex dynamic phenomenon in coal mines. During the outburst, a large amount of coal and considerable gas is ejected to the roadway or stope in a very short period, resulting in a very huge dynamic effect. It is considered to be a geological disaster that seriously threatens safe production in coal mines.1–3 Coal seam uncovering is a relatively dangerous link in coal mining and poses the greatest harm. In addition, due to factors such as high outburst intensity and special technology, the frequency of uncovering-induced outburst accidents is also the highest.4,5 According to statistics, uncovering-induced coal and gas outburst accidents account for about 45% of the total outburst accidents in China. Moreover, more than 80% of the major outburst accidents occur in the process of coal uncovering at crosscuts, with an average outburst strength of 586.1 t. In 2009, a particularly serious coal and gas outburst accident occurred in Tonghua Coal Mine, Chongqing, ejecting 3000 t of coal and 282,000 m³ of gas and resulting in 30 deaths and 79 injuries. A total of 263 gas outburst accidents have occurred during coal uncovering in Zijiang Coal Mine, Hunan Province. In 2005, a coal and gas outburst accident occurred during coal uncovering in the mine, ejecting 1200 t of coal and causing 22 deaths. A total of 15 uncovering-induced outbursts have occurred in Hongling Coal Mine, Liaoning Province, leading to 43 deaths. The most serious accident occurred in 1996, which ejected 5390 t of coal and abnormally emitted 420,420 m³ of gas. The coal was thrown out for nearly 400 m by strong airflow, and 14 people died.

Radial boreholes, a common mining technology used in coalbed methane (CBM) development, are horizontal wells whose curvature radii are smaller than those of conventional boreholes.6,7 Through high-pressure hydraulic jet drilling, the borehole diameter and length can reach 30–50 mm and 50–150 m, respectively. Academic research on radial borehole...
mining technology mainly focuses on the field of CBM production, including the crack expansion mechanism, plugging removal, production stimulation, crack development law, etc., during fracturing.8,9 Radial boreholes can control the direction of fracture initiation and expansion and communicate with or affect the target coal seam through radial branch boreholes. In addition, the energy loss of fractured formation during hydraulic fracturing can be reduced by the guide function of radial boreholes. In this way, greater damage can be caused to the coal seam in the target area for promoting CBM production. The technological application of directional coal uncovering through radial boreholes is still rarely reported.

In recent years, scholars at home and abroad have successively adopted the methods such as gas extraction, hydraulic punching, metal skeleton, deep-hole presplitting blasting, and coal seam acidizing for outburst prevention during coal uncovering in crosscuts (vertical and inclined shafts).10−15 Gas extraction is to accelerate gas emission in an outburst dangerous coal seam by increasing the gas pressure gradient through negative pressure (lower than atmospheric pressure) generated by mechanical external force. This method is suitable for gently inclined coal seams and is pretty safe. However, due to long gas extraction time, the coal uncovering period usually lasts more than 5 months. Hydraulic punching prevents coal and gas outburst by reducing the gas content in a coal seam and altering the stress state of the coal seam. This method is applicable to relatively hard coal. If it is applied to a soft coal seam, the proppant tends to be embedded in coal and then loses its supporting function. Meanwhile, the fracturing fluid is not easy to be removed after entering the coal seam. In short, this method is notably influenced by the physical properties of the coal seam. The metal skeleton serves to increase the stability of coal above the roadway and discharge gas in coal during coal uncovering in crosscuts (vertical and inclined shafts). This method is suitable for inclined and steeply inclined coal seams with low outburst risk. It is difficult to construct a metal skeleton in gently inclined seams, and there is a lack of a unified method of reasonable parameter calculation. Hence, its application scope is also rather limited. Deep-hole presplitting blasting avails the formation of a controllable fracture network by means of shock wave and high-pressure gas produced by explosive explosion in a coal seam, thus turning absorbed gas in coal seams into free gas through vibration. In this way, the drainage effect is improved, and the stress distribution of the coal seam is changed. Although this method is the most commonly adopted for coal uncovering, it is rather sophisticated with a cumbersome operational procedure. In addition, it requires a large-scale blackout during blasting, which affects the production of adjacent working face. At present, the application of outburst prevention measures for coal uncovering in crosscuts at home and abroad is facing many problems such as complex construction technology, long period of coal uncovering, low speed, and outburst during coal uncovering. These existing methods can hardly meet the needs of rapid, efficient, and safe coal uncovering in modern mines, which seriously threatens safe production and benefit of mines. A new coal uncovering technology that can both ensure the need of safety and benefit and achieve the goal of efficient and economic coal uncovering is in urgent need.

To solve many existing problems in coal uncovering, we proposed a multibranch radial borehole hydraulic fracturing (MRBHF) coal uncovering technology in the CBM well by taking Zhaozhuang Coal Mine as an example. This technology is different from traditional coal uncovering methods in light of the gas control strategy. Furthermore, the technology was
applied to engineering on site. The successful application of this method proves that it boasts advantages such as short uncovering period, high safety, excellent economic benefit, convenience, and practicality, compared with conventional uncovering measures. This method can provide new ideas and approaches for gas control in other coal mines at home and abroad.

OUTBURST PREVENTION DURING COAL UNCOVERING

Process of Coal Uncovering. Shaft coal uncovering is a common uncovering method in crosscuts of coal mines. During the uncovering, outburst prevention is essential for mine construction. When the working face of the shaft approaches the coal seam, a funnel-shaped mining pressure relief zone (i.e., a maximum pressure relief zone in the center surrounded by partial pressure relief zones) will be formed in the front (i.e., the bottom) of the working face, and stress will concentrate around the shaft and in the front of the working face. It is necessary to adopt targeted shaft coal uncovering measures in accordance with the characteristics of stress distribution so as to ensure the safety of coal uncovering there. National Coal Mine Safety Administration of China has regulated in detail the process and procedure of coal uncovering in Regulations on Prevention and Control of Coal and Gas Outburst. Currently, the relatively commonly used method is the “three-step method” shaft coal uncovering technology (see Figure 1). The procedure is as follows: First, the gas pressure is detected and measured in advance at a distance of 10 m (20 m for the complex geological structure belt) from the coal seam. Second, the outburst index of the uncovering face is predicted and tested at distances of 7, 5, and 1.5–2 m from the coal seam. Third, the coal seam is uncovered by using a long-distance vibration blasting at a distance of 1.5–2 m from the coal seam. The discharge boreholes, with spacing smaller than 2 m, are constructed 8 m away from the shaft wall. When the gas content lowers to a safe range, the coal seam is uncovered by using the vibration blasting.

Analysis of Coal and Gas Outburst Process. Underground coal mining destroys the stress balance in the original formation and redistributes the stress in coal. Generally speaking, within the short period after mining space formation, a high stress concentrates near the critical surface of mining space. When the value of concentrated stress reaches the strength limit of coal, the coal in this region undergoes yield deformation first, and then the concentrated stress is transferred to the deep part of coal consequently. After the stress balances, the coal in the front of mining space will form a pressure relief zone, a stress concentration zone, and an original stress zone. In most cases, the stress in coal in the pressure relief zone close to the mining space is lower than the original stress, and it can be considered that the stress in coal subjected to plastic deformation in the pressure relief zone and the stress concentration zone is in a state of limit equilibrium. After the working face advances for a certain distance, the stress state of coal in the front of the working face suddenly changes. The stress acting on the coal in the pressure relief zone and the concentration stress zone will transfer to coal in the deeper part. That is, the pressure relief zone and the stress concentration zone, together with the peak of concentrated stress, both advance with the excavation. Therefore, the coal in the front of the working face will inevitably experience a rise from the original stress state to the stress concentration state. As a result, stress will concentrate in the gas-bearing coal for a short period. Meanwhile, a pressure relief zone of the fractured belt will be formed in the front of the newly exposed coal wall; the lower the coal strength is, the larger the fractured zone is. The gas-bearing coal, which begins to enter the transient and stable rheology, will undergo accelerated deformation and failure under the action of sharply increased concentrated stress so that the coal in the last rheological stage will be further broken. If the accumulated gas internal energy works at this time, it can crush the broken coal and throw coal powder out. Accordingly, coal and gas outburst will occur (see Figure 2).

Gas in coal exists in the fracture space in two forms: free gas and adsorbed gas of which the amount of adsorbed gas accounts for 80–90% of the total amount. Hence, gas adsorption and desorption will affect the flow of gas flow. According to the deformation and failure mechanism of modern rock, the deformation and failure process of coal rock is dominated by the initiation and propagation of internal cracks and fractures, while the role of confining pressure is to prevent the initiation and propagation, i.e., to prevent rock failure. The mechanical action of gas pressure is also equivalent to the confining pressure. Laboratory macroscopic experiments have revealed that the effect of gas pressure on the mechanical response and mechanical properties of coal rock is jointly brought by adsorbed gas and free gas. As for the effect of gas pressure on the adsorption capacity of a certain coal, the strength of coal rock mass will decrease with the rise of gas pressure; the higher the gas pressure is, the smaller the elastic modulus is. The evolutional relationship between an outburst coal seam and a non-outburst coal seam is shown in Figure 3.
Outburst Prevention during Shaft Coal Uncovering. There are four types of outburst during coal uncovering in crosscuts: outburst occurring while coal seam blasting and uncovering, delayed outburst, outburst occurring while crosscut crossing, and outburst that breaks through the rock pillar. Among the four, the first accounts for the largest proportion. Outburst during coal uncovering in crosscuts, which may occur while blasting, coal uncovering, and crosscut crossing, is characterized by high strength and high frequency. Among dozens of super-large outbursts in China, 75.9% occurs during coal uncovering at crosscuts. If gas in a coal seam is not discharged before coal uncovering there or if the gas pressure remains high after the discharge, then continuous outburst may occur: the moment the coal seam is blasted and uncovered, the pressure state of the outburst coal seam is destroyed. Due to the large gradient of inside gas pressures and outside ones, the internal coal is also exposed. By the same token, the newly exposed coal is destroyed under high gas pressure, and the internal coal is also exposed. Such interlocking coal breakage and ejection enables outburst phenomena like rib spalling may occur rather than outburst during the creep stage of accelerated destruction after the peak, only depressurize the entire crosscut range in the front of the working face. In this way, even if the coal deformation enters the pressure relief zone cannot be extended to the deeper coal and induces continuous outburst. During coal uncovering in crosscuts, because of the obstruction and support of the pressure relief zone, the coal with outburst risk outside the pressure relief zone cannot be exposed and is not likely to undergo outburst. However, the coal with outburst risk is located in the stress concentration zone or the original stress zone with high ground stress and high pressure where gas is not easy to leak. If it is not timely supported after coal uncovering in crosscuts, then the partial fractured zone around the roadway will gradually fail, lose support, and fall suddenly. If the fall/caving causes the sudden exposure of the outburst coal seam, then delayed outburst will occur. The uncovering face at crosscut is jointly affected by high gas pressure and high ground stress as it advances. If the newly exposed coal is not supported with sufficient strength in time, the defense barrier around the shaft is not enough to resist the joint force, and outburst accidents can easily occur once there is an external force disturbance. As can be observed from the stress distribution in Figure 4, the uncovering face is directly located above the pressure relief and stress concentration zones where the outburst risk is low. However, the superimposed area of horizontal and vertical stresses is especially prone to outburst as the stress is the highest and the support is the weakest in this location. Based on the above analysis, during coal uncovering, first, high-strength gas drainage measures must be taken to fully depressurize the entire crosscut range in the front of the working face. In this way, even if the coal deformation enters the creep stage of accelerated destruction after the peak, only phenomena like rib spalling may occur rather than outburst due to the full release of gas and the strength of coal rock. Second, it is necessary to control the gas supply from both sides of the crosscut working face to the front of it so as to control delayed outburst and outburst occurring while crossing the crosscut.

Engineering Background. Gas Occurrence. Zhaozhuang Coal Mine is located in the south of Qinshui coalfield in Shanxi Province, China (see Figure 5). The minefield is 16.65 km long from north to south and 14.80 km wide from east to west, covering an area of 144.13 km². Coal-bearing strata in the minefield are mainly the upper Carboniferous Taiyuan formation (C3t) and the lower Permian Shanxi formation (P1s). Among a total of 14 coal seams, the no. 3 coal seam with a thickness of 5.2 m and a dip angle of 3°–5° is the primary mining coal seam at present. Its roof is mainly composed of mudstone and sandy mudstone, with some siltstone and a little medium and fine sandstone; and its floor is also mainly composed of mudstone and sandy mudstone, with some medium and fine sandstone and siltstone. The maximum absolute gas emission of the mine is 395.6 m³/min. The mine...
contains five panels among which panels 1, 3, and 5 are production panels, while panels 2 and 4 are preparation panels. The complex gas geological structure of the mine leads to extremely uneven gas accumulation in different panels. The gas content in panel 1 is the highest (about 21 m$^3$/t), followed by that of panel 3 (8−12 m$^3$/t), and that of panel 5 is the lowest (below 7 m$^3$/t). The coal seam is generally of poor permeability and fast attenuation, making it difficult to drain gas from it. The basic parameters of gas are listed in Table 1.

### Coal Uncovering Area

In Zhaozhuang Coal Mine, panels 1, 3, and 5 are mined first. Considering the mining needs in the later period, it is planned to develop panel 2 as the next mining panel. To realize independent ventilation, an intake air shaft and a return air shaft are arranged in panel 2 (see Figure 6). The return air shaft adopts the conventional cross-measure borehole drainage measure to uncover coal, while the intake air shaft adopts the MRBHF to uncover coal. The intake air shaft has a depth of 784.5 m, a vertical depth of 730.45 m, and a net diameter of 8.5 m. Its wall is constructed by cast-in-place

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**Figure 5.** Gas content and geological structure of Zhaozhuang Coal Mine.

**Table 1.** Coal Seam Gas Parameters of Zhaozhuang Coal Mine

| Lithology  | mudstone | No. 3 coal seam | sandy mudstone | medium grain sandstone | sandy mudstone | fine-grained sandstone | sandy mudstone | Silurian |
|-----------|----------|-----------------|----------------|-----------------------|----------------|-----------------------|----------------|---------|
| Thickness | 7.2      | 4.7             | 4.8            | 6.2                   | 9.1            | 6.6                   | 12.9           | 8.5     |

Table 1. Coal Seam Gas Parameters of Zhaozhuang Coal Mine

| content (m$^3$/t) | panel | 1 | 2  | 3 | 4 | 5 |
|-------------------|-------|---|----|---|---|---|
|                  |       | 13−20 | 15−25 | 8−13 | 13−16 | 4−7 |
| pressure (MPa)    |       | 0.57−0.61 | 1.0−1.08 | 0.51−0.52 | 0.54−0.58 | 0.21−0.33 |
| gas flow in 100 m borehole (m$^3$/min hm) | | | | | | |
| borehole gas attenuation coefficient ($D^{-1}$) | | | | | | |
| coal seam permeability coefficient (MPa$^2$ d) | | | | | | |
| initial velocity of gas release ($\Delta P$) | | | | | | |
| firmness of coal ($f$) | | | | | | |
| vertical thickness from the roof to the ground (m) | | | | | | |

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expressed by the stress deformation characteristics of coal and rock are typically deformation and strength characteristics of the rock. The mechanical properties of coal and rock mainly refer to the corresponding physical and mechanical properties. The shear strength or Young's modulus, and Poisson's ratio; that of siltstone is 16.44 and 14.77 times the uniaxial compressive strength of coarse sandstone is 14.78 times the tensile strength; that of siltstone is 16.44 and 14.77 times; that of sandy mudstone is 23.62, 26.96, and 13.33 times; that of limestone is 11.19 times; and generally that of coal is approximately 4-6 times. It can be seen that the ratio between uniaxial compressive strength and tensile strength of noncoal rock is quite large, at more than 15 times as a whole, while the proportion relationship between coal and rock is small. The existence of this relationship between coal and rock indicates that rock is more prone to tensile failure under external force. Simonson33 and Hanson34 studied the influence of lithology on hydraulic fracturing from the perspective of stress intensity factor. The study of linear elastic fracture mechanics shows that the stress field and strain field near the crack tip are directly proportional to the “stress intensity factor” K at the crack tip. When the stress intensity factor reaches the critical value K*, then the crack will expand unstably. K* is a material constant, which is also referred to as fracture toughness.

\[ K^* = \frac{2E\gamma}{\sqrt{\pi L}} \]

where \( E \), \( \nu \), and \( \gamma \) are the elastic modulus, Poisson’s ratio, and specific surface energy of the rock, respectively.

According to the theory of linear elastic fracture mechanics, the stress intensity factor of the vertical crack is determined as follows:

\[ K = (P - \sigma_z)\sqrt{\pi L} \]

The intensity factors of horizontal cracks are determined as follows:

\[ K = \frac{2}{\pi}(P - \sigma_z)\sqrt{\pi L} \]

In the above formula, \( \sigma_x, \sigma_y, L, \) and \( P \) respectively represent the minimum principal stress in the horizontal direction, the ratio of the uniaxial tensile strength to the uniaxial compressive strength of the rock, and the length of horizontal crack. The following relationship exists between the uniaxial compressive strength and tensile strength of roof and floor rocks in the no. 3 coal seam of the Zhaozhuang Coal Mine: the uniaxial compressive strength of coarse sandstone is 14.78 times the tensile strength; that of siltstone is 16.44 and 14.77 times; that of sandy mudstone is 23.62, 26.96, and 13.33 times; that of limestone is 11.19 times; and generally that of coal is approximately 4-6 times. It can be seen that the ratio between uniaxial compressive strength and tensile strength of noncoal rock is quite large, at more than 15 times as a whole, while the proportion relationship between coal and rock is small. The existence of this relationship between coal and rock indicates that rock is more prone to tensile failure under external force. Simonson33 and Hanson34 studied the influence of lithology on hydraulic fracturing from the perspective of stress intensity factor. The study of linear elastic fracture mechanics shows that the stress field and strain field near the crack tip are directly proportional to the “stress intensity factor” K at the crack tip. When the stress intensity factor reaches the critical value K*, then the crack will expand unstably. K* is a material constant, which is also referred to as fracture toughness.

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\[ K = \frac{2}{\pi}(P - \sigma_z)\sqrt{\pi L} \]
minimum principal stress in the vertical direction, the fracture height, and the fracturing fluid pressure. When the crack expands in an unstable manner, then the pressure for expanding the crack can be obtained from formulas 1−3 as follows:

For vertical cracks:

\[ P = \sigma_2 + \sqrt{\frac{2E\gamma}{\pi L(1 - \nu^2)}} \]  

\[ (4) \]

For horizontal cracks:

\[ P = \sigma_1 + \sqrt{\frac{2E\gamma}{\pi L(1 - \nu^2)}} \]  

\[ (5) \]

According to formula 1, when the elastic modulus E2 of the adjacent rock stratum is much smaller than the elastic modulus E1 of the fractured layer, then the fracture approaches to the interface, leading to the continuous expansion of \( K_1 \) at its end. The closer the fracture is to the interface, the more easily it may expand and finally extend to the adjacent rock stratum through the interface. On the contrary, when the elastic modulus E2 of the adjacent rock layer is much larger than the elastic modulus E1 of the fractured layer, as a result of \( K_1 \to 0 \) at the end, higher liquid pressure \( P \) is required. This means that the fracture cannot expand to the adjacent layer, and the adjacent rock layer blocks the propagation of the fracture in the fractured layer and finally causes the fracture to terminate at the interface. Due to the complex composition of the coal seam surrounding rock in the coal uncovering area, sandstone and sandy mudstone occur alternately. It can be seen from Table 2 that the rock mass strength is in the form of “weak-strong-weak”. The roof above the coal seam in the coal uncovering area mainly consists of sandstone, with a rock thickness of 9.33 m and a spacing of about 12.0 m. The rock mass strength and thickness are high, which can effectively hinder the effective expansion of the fracture, and the old bottom under the coal seam is mainly composed of sandstone. The main reason for this is that the rock thickness is as high as 18.63 m, the coal rock spacing is about 7.2 m, the rock mass strength is high, and the thickness is large, which together can also hinder the effective expansion of the fracture. The fracture can only be produced and extended in an effective interlayer and is controllable to a certain extent. At the same time, the main goals of the coal seam fracturing are to increase the permeability of the coal seam, then to extract and discharge gas, release pressure, and finally uncover the coal in the shaft.

**Necessity Analysis.** The ZZFT-013 well, with 43.85 m of linear distance from the inlet air shaft, is a vertical well for

**Figure 8. Curve of fracturing construction of the no. 3 coal seam in the ZZFT-013 CBM well.**

| sample depth  | rock types          | bulk density | compressive | tensile | shear resistance | elastic modulus (10^6 MPa) | softening coefficient | Poisson’s ratio |
|---------------|---------------------|--------------|-------------|---------|-----------------|---------------------------|----------------------|-----------------|
| 707.40−707.86 | coarse sandstone    | 2.58         | 41.1        | 2.78    | 3.57            | 2.8474                    | 0.73                 | 0.34            |
| 709.30−713.9  | siltstone           | 2.73         | 31.6        | 2.14    | 3.57            | 4.5455                    | 0.73                 | 0.12            |
| 716.70−716.85 | fine sandstone      | 2.84         | 43          |         |                 |                           | 0.73                 | 0.25            |
| 717.00−722.07 | sandy mudstone      | 2.62         | 28.2        | 1.68    | 3.44            | 1.3132                    | 0.91                 | 0.22            |
| 724.30−724.61 | fine sandstone      | 2.8          | 52.8        | 2.66    | 5.12            | 3.7761                    | 0.18                 | 0.14            |
| 725.85−727.13 | medium sandstone    | 2.63         | 69.3        | 2.36    | 6.96            | 3.3045                    | 0.18                 | 0.12            |
| 735.80−736.75 | sandy mudstone      | 2.53         | 11.1        | 0.47    | 4.63            | 1.3132                    | 0.18                 | 0.14            |
| 737.30−738.31 | siltstone           | 2.64         | 26.3        | 1.6     | 2.69            | 4.5455                    | 0.26                 | 0.12            |
| 741.60−742.30 | sandy mudstone      | 2.63         | 12.4        | 0.46    | 1.19            | 1.3132                    | 0.26                 | 0.12            |
| 744.80−745.07 | fine sandstone      | 2.58         | 13.2        | 1.95    | 1.91            | 3.7761                    | 0.26                 | 0.12            |
| 752.20−752.33 | limestone           | 2.78         | 21.2        |         |                 |                           | 0.12                 | 0.12            |
| 764.80−765.80 | limestone           | 2.68         | 39.4        | 3.52    | 8.17            | 6.8786                    | 0.1                 | 0.12            |
| 767.20−767.42 | sandy mudstone      | 2.58         | 5.2         | 0.39    | 1.54            | 1.3132                    | 0.25                 | 0.18            |
surface CBM exploitation constructed in 2011. The well was hydraulically fractured in May 2011. According to the effect of hydraulic fracturing then, it is feasible to investigate whether the fracturing range of the ZZFT-013 well affects the range of coal seam uncovering in the intake air shaft and to further determine whether it is necessary to carry out MRBHF in the ZZFT-013 well. The curve of the fracturing effect before CBM exploitation is exhibited in Figure 8.

The actual volume of fluid injected into the ZZFT-013 well is 545.6 m$^3$. In addition, 20.0 m$^3$ of 0.45−0.9 mm quartz sand and 10.0 m$^3$ of 0.8−1.2 mm quartz sand are added. The actual volume of sand filling satisfies the designed volume. The construction pressure is 10.63−6.85 MPa (see Figure 8). Through real-time monitoring of fracture length and azimuth angle, we found that the main fracture development direction is about 63° in the northeast, and the line connecting centers of the intake air shaft and ZZFT-013 CBM well shares an angle of 81° with the main fracture direction. The fractures perpendicular to the main fracture direction do not develop obviously, and their development range is about 35 m, which approximately equals the maximum development range of fractures in the ZZFT-013 CBM well in the first ordinary fracturing (see Figure 9).

The linear distance between the ZZFT-013 well and the intake air shaft is 43.85 m, and the probability that fractures in the ZZFT-013 well affect the center of the intake air shaft is relatively small. If the ZZFT-013 well is subjected to ordinary secondary fracturing again for enhancing the coal permeability in the uncovering area, it is probably for the fractures to extend along the direction of the main fracture that has been formed during the first fracturing, thus failing to affect the uncovering area in the intake air shaft. Therefore, it is necessary to construct guiding radial boreholes for the CBM well so as to expand the influence range of fractures.

**Designed Fracturing Parameters.** Considering the dip angle (3−15°) of the coal seam in the area, the first branch borehole is drilled radially in the direction of the intake air shaft with a designed azimuth angle of 143°, at the position that is 2 m from the bottom of production casing of the ZZFT-013 CBM well (about 730.54 m). Then, another radial branch borehole is added every 0.4 m upward. A total of 8 branch boreholes (with a length of 43.85 m and a diameter of 50 mm) are constructed in the following sequence: ① → ② → ③ → ④ → ⑤ → ⑥. The designed parameters of radial boreholes are given in Table 3, and the schematic diagram of radial boreholes in the ZZFT-013 CBM well is shown in Figure 10.

### Table 3. Designed Parameters of Multibranch Radial Boreholes

| Operation Level | Construction Number | Working Depth (m/m/m) | Design Azimuth (°) | Design Length (m) |
|-----------------|---------------------|-----------------------|-------------------|------------------|
| Level 1         | ①                   | 727.94                | 143               | 43.85            |
| Level 2         | ②                   | 728.34                | 143               | 43.85            |
| Level 3         | ③                   | 728.74                | 143               | 43.85            |
| Level 4         | ④                   | 729.14                | 143               | 43.85            |
| Level 5         | ⑤                   | 729.54                | 143               | 43.85            |
| Level 6         | ⑥                   | 729.94                | 143               | 43.85            |
| Level 7         | ⑦                   | 730.34                | 143               | 43.85            |
| Level 8         | ⑧                   | 730.74                | 143               | 43.85            |

**Figure 9.** Maximum development range of fractures in the ZZFT-013 CBM well in the first fracturing.

**Figure 10.** Schematic diagram of radial boreholes in the ZZFT-013 CBM well.

In this work, directional fracturing is conducted on the bottom coal seam of the intake air shaft through the ZZFT-013 CBM well and eight radial branch boreholes. The ZZFT-013 CBM well is 760 m in depth upon completion of drilling, the casing depth is 732.54 m, the buried depth of the coal seam is 733.04−738.03 m, and the well is completed with an uncased hole. To prevent the fracture from extending in the direction of the original main fracture, the section below 732 m should be pretreated in advance. Thus, the workover truck is used to detect the sand surface of the ZZFT-013 CBM well and drill through-hole. The through-hole wall is scraped, and the well bottom is filled with sand to the end of the casing. Next, the end of the casing is sealed and fixed to 732 m by a bridge plug or cement after which horizontal radial branch boreholes are drilled and perforated (see Figure 11).

**Coal Powder Flowback.** In the process of radial borehole construction, the casing opening and jetting operation of a certain radial branch borehole is completed first, and then the oil pipe is lowered by 10−15 mm. Meanwhile, the steering gear is lowered 10−15 mm below the borehole by means of logging positioning. After the orientation and position are adjusted, the second casing milling and opening operation is conducted. The two boreholes are integrated to increase the cross-sectional area of the casing milling and opening and expand the passage from the radial branch borehole to the casing wall, thereby promoting the ability of coal powder flowback. After the completion of the second borehole, the original high-pressure injection nozzle on the jet pipe string is replaced by a high-displacement coal powder discharge nozzle. Afterward, the jet pipe string is again lifted up by 10−15 mm (see Figure 12) to the position of the completed branch borehole to carry out the second injection operation on the whole. The coal powder discharge nozzle is stuck into and withdrawn from the borehole several times to increase the amount of coal powder...
flowback and improve the effect of radial borehole hydraulic jetting. The construction is completed in turn.

**Fracturing Scheme.** Based on the related geological parameters of the no. 3 coal seam in Zhaozhuang Coal Mine, orthogonal experiments were performed to simulate and analyze the fracturing with different fluid volume and sand volume parameters on FracproPT software. In the interface of FracproPT software, the data needed for the design were inputted in turn step by step. These data mainly included pressure, temperature, proppant performance, perforation condition of target formation, well structure, characteristics and types of coal reservoir, filtration coefficient of fracturing fluid, etc. (see Table 4). The length and height of the fracture were simulated and analyzed.

The fracturing of the no. 3 coal seam in Zhaozhuang Coal Mine with different sand volumes and total fluid volumes was simulated on FracproPT software. The simulation results indicate that after the fracturing (see Table 5), the resultant fracture within the range of effective support height should be at least 12 m long. The half-length of the fracture should reach 65 m because the distance between the CBM well and the vertical shaft is 43.85 m, the effective gas outburst elimination area should be 12 m away from the outer contour of the shaft, and the diameter of the shaft is 8.5 m.

According to the simulation results (see Figure 13), the optimal scheme that enhances the permeability of the coal seam in the uncovering area of the intake air shaft is Scheme 4. The expected influence range of MRBHF is illustrated in Figure 14.

According to the diagram of the expected effect, when Scheme 4 is adopted for fracturing in the ZZFT-013 CBM well, the support fracture height and the fracture length can completely affect the coal seam and overlying strata in the
intake air shaft and meet the requirements of permeability enhancement.

**Directional Hydraulic Fracturing.** The use of the ZZFT-013 CBM well and eight radial branch boreholes realizes directional fracturing of the coal seam at the bottom of the intake air shaft. It shortens the time of pre-extraction for coal uncovering and achieves the safe and rapid uncovering of the outburst coal seam. The construction procedure of radial borehole fracturing in the coal reservoir is presented in Figure 15.

Before the operation of the radial well, the ZZFT-013 CBM well should be subjected to workover, casing scraping, and well

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### Table 5. Parameters and Results of Numerically Simulated Fracturing Scheme

| proposed scheme | fracturing fluid | volume of liquid (m³) | volume of sand (m³) | length of simulated support fracture (m) | height of upper half fracture (m) | height of lower half fracture (m) |
|-----------------|------------------|-----------------------|---------------------|------------------------------------------|----------------------------------|----------------------------------|
| Scheme 1        | clear water      | 700                   | 5                   | 78.7                                     | 6.6                              | 12.9                             |
|                 | activated water |                       |                     | 113.6                                    | 15.2                             | 12.9                             |
| Scheme 2        | clear water      | 400                   | 10                  | 41.1                                     | 8.3                              | 5.4                              |
|                 | activated water |                       |                     | 41.1                                     | 8.3                              | 5.4                              |
| Scheme 3        | clear water      | 500                   | 10                  | 58.2                                     | 12                               | 9.6                              |
|                 | activated water |                       |                     | 61.4                                     | 13.3                             | 9.6                              |
| Scheme 4        | clear water      | 600                   | 10                  | 78.1                                     | 11.6                             | 8.6                              |
|                 | activated water |                       |                     | 86.7                                     | 13.8                             | 8.6                              |

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**Figure 13.** (a–d) Simulated diagram of optimum selection of parameters for four fracturing schemes.
washing operation, in order to ensure that the guide with the maximum outer diameter of 117.5 mm can be smoothly set into the target coal seam section and that there is no drilling mud and other debris and impurities on the inner wall of well casing. The main construction steps are as follows: lowering the guide, correcting the depth and orientation of the guide outlet with the aid of magnetic positioning and natural gamma meter logging, correcting the orientation of the guide outlet with the aid of gyroscope, setting the milling tool string for casing drilling and milling, radial branch borehole drilling and construction by a jet, fracturing, etc. Before fracturing, the following preparation should be made: 12 sets of 50 m³ liquid storage tank, 600 m³ of fracturing fluid (finely filtered water added with 300 kg of ALD-608 and 300 kg of XLD-108), and vertical sand tank equipped with 20 m³ of 0.45−0.9 mm quartz. Meanwhile, the main fracturing vehicle, instrument vehicle, pipe conveyor, sand mixing vehicle, and auxiliary fracturing equipment are in place (see Figure 16). The perforation employs the means of cable perforation and the 102 mm perforating gun, which carries 127 mm perforating charge. The operation lies at the level of 726.5−729.5 m and is 3 m-thick. The hole density is 24 holes/m, and a total of 72 holes are perforated with a perforation rate of 100%. The curve of fracturing in the ZZFT-013 CBM well is shown in Figure 17.

The fracturing operation in the ZZFT-013 CBM well started on November 3, 2014. At 9:57, the secondary fracturing started. In this process, 283.88 m³ of prepad fluid was injected, with the construction pressure and displacement being 6 MPa and 7.92 m³/min, respectively. At 10:33, 223.46 m³ of sand-carrying fluid was injected, consuming 11.89 m³ of 0.45−0.9 mm quartz sand, with the construction pressure and displacement being 6.4 MPa and 8.97 m³/min, respectively. At 10:58, 8.96 m³ of displacing fluid was injected. At 11:59, the pump was turned off at the pressure of 0.17 MPa, which marked the end of fracturing. The total volume of injected fluid, the average sand ratio, and the construction displacement are 516.3 m³, 5.3%, and 0.15−9.07 m³/min, respectively. During the fracturing, multiple fractures are observed in the middle of the well bottom, and the stratum at the well bottom bulges obviously for 500−600 mm. Moreover, there are many fractures on the well wall, indicating the remarkable enhancement in the permeability of the coal seam. By observing the ZZFT-013 CBM well from the ground, intermittent flowing of gas is found at the wellhead, suggesting that the amount of gas emission increases significantly.

## RESULTS AND DISCUSSION

### Gas Drainage

After the completion of ground fracturing construction, the gas drainage borehole is constructed within the inlet air shaft for speeding up drainage of coal seam gas and accelerating coal uncovering in the intake air shaft. A ZWY-60 mobile pumping station is installed on the ground (more than 50 m away from the air shaft head), and a 159 mm seamless steel pipe is used as the pumping pipeline. The SGZX-3 drilling rig is employed here. The drill pipe is 50 mm in diameter and 2.1 m/section, while the drill bit is 94 mm in diameter. All the gas drainage boreholes penetrate the no. 3 coal seam and reaches 0.5 m below the coal seam floor. The boreholes cover the coal seam that is within 18 m from the centerline of shaft. The arrangement of gas drainage boreholes in the intake air shaft is shown in Figure 18.

According to the actual situation, 46 boreholes are drilled at a normal distance of 7.5 m from the coal seam roof. The lengths of the first, second, and third rings of boreholes are...
12.9, 13.4, and 14.3 m, respectively. The construction parameters of drainage boreholes in the intake air shaft are listed in Table 6.

**Effect Test.** Eight boreholes for testing the regional drainage effect are drilled at the normal distance of 7 m. The test is mainly verified by the gas content index. If the regional drainage measures are validated, the next step of the coal uncovering process will be carried out. If they are tested to be invalid, the measures will continue until they become validated.

Before the normal distance between the working face and the coal seam becomes smaller than 5 m, the risk of coal seam outburst is predicted. The measuring points are arranged both in the middle and in the surrounding of the shaft to determine the value of the gas desorption index $K_1$ of drill cuttings. For dry coal and wet coal, the critical values of $K_1$ are 0.5 and 0.4 mL/g min$^{1/2}$, respectively. Boreholes for testing the regional drainage effect are also drilled at the normal distances of 5 and 2 m (see Figure 19).

As suggested by the actual measurement, at the normal distance of 7 m, the gas content rises from the shaft center to the both sides, and the maximum and minimum values obtained by the regional measure effect test are 7.49 and 5.15 m$^3$/t, respectively. At the normal distance of 5 m, the measured maximum and minimum values of $K_1$ are 0.31 and 0.18 mL/g min$^{1/2}$, respectively. At the normal distance of 2 m, the measured maximum and minimum values of residual gas contents are 6.89 and 5.83 m$^3$/t, respectively, and the measured maximum and minimum values of $K_1$ are 0.20 and 0.08 mL/g min$^{1/2}$, respectively (see Figure 20).

It can be seen that for both regional and local outburst risk predictions, the values of residual gas contents and $K_1$ are smaller than 8.0 m$^3$/t.

### Table 6. Construction Parameters of Drainage Boreholes in the Intake Air Shaft of Zhaozhuang Coal Mine

| borehole number | distance from the shaft center (m) | angle with the shaft center (°) | borehole length (m) | borehole number |
|-----------------|-----------------------------------|--------------------------------|---------------------|----------------|
| the first ring  | 1                                 | 3                              | 12.9                | 8              |
| the second ring | 2                                 | 14                             | 13.4                | 16             |
| the third ring  | 3                                 | 25                             | 14.3                | 22             |
and 0.4 mL/g min\(^{1/2}\), respectively. The measured values meet the requirements of safe coal uncovering and demonstrate the effectiveness of radial borehole hydraulic fracturing measures. Thus, the coal seam can be uncovered successfully.

**Effect Evaluation.** In Zhaozhuang Coal Mine, the intake air shaft adopts the radial wells to uncover coal, while the return air shaft adopts the conventional cross-measure borehole drainage measure to uncover coal. The two air shafts, which have the same geological environment, are located less than 500 m apart. To investigate the effect of directional hydraulic fracturing coal uncovering through radial boreholes, the comprehensive parameters and effects of different coal uncovering processes in the two shafts are compared (see Table 7).

From Table 7, compared with conventional measures, hydraulic fracturing through radial wells achieves a significantly improved drainage effect. Specifically, the actual period for coal seam outburst elimination shortens by 118 d, the growth rate of coal seam permeability reaches 721.6%, the indexes such as the extraction volume and rate are notably raised, the engineering quantities of 54 predrainage boreholes and 454 discharge boreholes are saved, the permeability of coal seam increases by 3.55 times, the gas drainage volume increases by 1.93 times, the investment of coal uncovering project is reduced, and the risk of coal seam outburst is greatly reduced.

**Table 7. Comparison between Effects of Measures Adopted in Intake and Return Air Shafts**

| parameter                                  | return air shaft                                                                 | intake air shaft                                      |
|---------------------------------------------|----------------------------------------------------------------------------------|-------------------------------------------------------|
| coal uncovering measure                     | conventional measures such as blasting                                           | directional hydraulic fracturing in radial wells      |
| engineering quantity                        | 54 predrainage boreholes, 500 discharge boreholes, 12,420 m of drilling, and 340 t of explosive | 8 radial boreholes, 46 discharge boreholes, and 632 m of drilling |
| gas drainage period for coal seam outburst elimination (d) | 158                                                                              | 40                                                    |
| outburst prevention index \(K_1\) max (mL/g min\(^{1/2}\)) | 0.42                                                                             | 0.24                                                  |
| initial gas content (m\(^3\)/t)             | 13.26                                                                            | 15.21                                                 |
| residual gas content (m\(^3\)/t)            | 7.65                                                                             | 7.16                                                  |
| gas reserves (m\(^3\))                      | 153,428                                                                          | 193,428                                               |
| gas drainage volume (m\(^3\))               | 63,672.62                                                                        | 123,020.2                                             |
| extraction rate (%)                         | 41.50                                                                            | 63.60                                                 |
| permeability coefficient of original coal seam (m\(^2\)/MPa\(^2\) d) | 0.162                                                                            | 0.162                                                 |
| permeability coefficient of enhanced coal seam (m\(^2\)/MPa\(^2\) d) | 0.375                                                                            | 1.331                                                 |
| growth rate of permeability coefficient of coal seam (%) | 131.48                                                                           | 721.6                                                 |
CONCLUSIONS

In China, the uncovering-induced coal and gas outburst accidents account for about 45% of the total outburst accidents, and over 80% of the major outburst accidents occur in the process of coal uncovering. In this study, a new method of coal uncovering is proposed with Zhaozhuang Coal Mine taken as an example. The main conclusions are summarized as follows:

(1) Coal and gas outburst occurring during coal uncovering is a chain dynamic phenomenon caused by multiple factors such as ground stress, gas pressure, and external disturbance of coal. Its occurrence and evolution are regular. To prevent coal and gas outburst accidents, we suggest to support the exposed coal in time and reserve rock pillars with sufficient thickness between the uncovering working face and the coal seam. This aims to promote coal strength, reduce the gas pressure gradient between the pressure relief zone and the stress concentration zone, and increase the ability of coal in the pressure relief zone to resist gas internal energy of deep coal.

(2) By taking Zhaozhuang Coal Mine as an example, the concept of MRBHF rapid coal uncovering technology is put forward and applied in practice. First, it is obtained through analysis that the distance between the intake air shaft and the constructed surface CBM well is pretty short. In addition, the necessity of constructing multibranch radial boreholes in the surface CBM well is analyzed. Furthermore, the construction and fracturing parameters of multibranch radial boreholes are determined, and coal powder flowback during the construction of radial boreholes is designed. Coal seam fracturing through multibranch radial boreholes results in more fractures around the borehole wall, obviously increased gas emission from the boreholes, and intermittent flowing of gas. It proves that multibranch radial borehole hydraulic fracturing can achieve the purpose of directional fracturing and permeability enhancement of coal in the uncovering area.

(3) The technology is verified to be effective by testing its core technology in the field. After applying the technology to the coal seam, the coal seam achieves a growth rate of permeability coefficient of 721%, a gas extraction rate of 63%, a gas extraction volume of 123,000 m³, and a coal uncovering period of only 40 d. Compared with the conventional uncovering measures adopted in the return air shaft, the technology shortens the uncovering period by 118 d, enhances permeability of the coal seam by 3.55 times, increases the gas drainage volume by 1.93 times, reduces 508 drainage boreholes, considerably decreases investment of coal uncovering project, and remarkably improves the drainage effect.

(4) Multibranched radial borehole hydraulic fracturing uncovering coal technology boasts the advantages of the strong guiding ability of the radial borehole and the long distance of directional hydraulic fracturing. By conducting fracturing of constructed radial boreholes in the CBM well, the technology increases fractures, enhances the coal permeability, and raises gas drainage volume in the uncovering area. It achieves safe, efficient, and economical coal uncovering and also improves the reuse efficiency of the surface CBM well. The successful application of this technology provides a certain reference for the coal uncovering operation in other mines.

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Notes

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