

Mining thin sub-layer as self-protective coal seam to reduce the danger of coal and gas outburst

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Received: 8 August 2013 / Accepted: 9 October 2013 / Published online: 18 October 2013
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Abstract In response to the severe situation of coal mine gas disaster in China, a new method of reducing the danger of coal and gas outbursts and improving gas drainage and utilization in coal mines was introduced in this paper. The main idea of this method is to mine thin sub-layer as self-protective coal seam to eliminate or reduce the danger of coal and gas outburst. This method can be implemented by drills along seam and hydraulic jet when the mined seam with a relatively weak risk of coal and gas outbursts is soft or has a soft layer. This method was first applied in the Yian mine to verify its effectiveness. The results of application showed that mining thin sub-layer as self-protective coal seam can effectively eliminate the danger of coal and gas outburst and improve gas drainage and utilization. As this method needs less time and lower cost than conventional protective layer mining, it is of great significance for mining coal seam with the danger of coal and gas outburst.

Keywords Coal mining · Self-protective coal seam · Thin sub-layer · The danger of coal and gas outburst

1 Introduction

In the years since the first reported coal and gas outburst occurred in the Issac Colliery, Loire coal field, France, in 1843 (Lama and Bodziony 1996), this hazard has occurred in most coal-producing countries and has posed a challenge to coal mine safety experts (Beamish and Crosdale 1998; Díaz Aguado and González Nicieza 2007a; Yang et al. 2012). Compared to mining activities worldwide, China has experienced the greatest frequency and intensity of outburst-related disasters (Cao et al. 2001). The results of a coal

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mine gas classification identification process found that in 2008, 647 coal mines in China were in danger of coal and gas outburst (State Administration of Coal Mine Safety of China 2009), and with the increase in mining depth of coal resources, by 2012, the number had increased to more than 800. Increased mining depths increase gas pressure and, combined with a complex set of geological conditions, result in increased rock and gas outbursts (Xue et al. 2011). More than 14,000 outbursts have occurred throughout north-eastern, eastern, southern and central China, and over 200 collieries have experienced these events (Cao et al. 2003). The death toll for the coal and gas outbursts from 2006 to 2010 is 1199 (Wang et al. 2014). According to official statistics, 17 major accidents related to coal and gas outbursts occurred in coal mines in China in 2009, leading to the deaths of 81 people (State Administration of Coal Mine Safety of China 2010).

There are several ways to control and prevent coal and gas outbursts, such as reducing the pressure of the mining seams and increasing the permeability of the mining seams using high-pressure hydraulic jets, drilling boreholes for gas drainage and infusing water and extracting protective coal seams (Flores 1998; Noack 1998; Díaz Aguado and González Nicieza 2007b; Lu et al. 2009; Tian and Zheng 2011). Mining protective coal seams is an effective and economical way to achieve protection from outbursts as well as improve gas drainage and utilization underground by reducing the pressure of the mining seams and increasing the permeability of the mining seams (Braüner 1994; Lama and Bodziony 1998; Yang et al. 2011). The main idea of the technique is to first mine a coal seam with a low risk of coal and gas outburst, which serves to relieve the stress in the protected coal seam and improve the gas permeability of the protected coal seam (Yang et al. 2011). China's current regulations for controlling coal and gas outbursts provide that, if possible, measures for protective coal seams must be given priority to mining coal seams that pose dangers of coal and gas outbursts (State Administration of Work Safety of China 2009; Liu et al. 2011). However, these measures can be implemented only under certain conditions. An appropriate protective layer must exist, and the protective layer itself must be easily exploited. Unfortunately, there are no appropriate protective layers for many coal seams in danger of coal and gas outbursts in China, and the protective layers require long exploitation periods, which require the investment of considerable personnel and material. To reduce the cost and time associated with mining protective layers and overcoming the limitations to the extraction of protective layers, a new method for extracting protective layers must be found.

2 Mining technology

Mining thin sub-layer as self-protective coal seam by drills along seam and hydraulic jet is a new technology of mining protective coal seam. As the most operations of this technology are implemented in coal seam, considering the efficiency of the mining by hydraulic jet and the security of the operations, this technology is only suitable for the soft coal seams and the coal seams which have a soft layer which have a relatively weak risk of coal and gas outburst. The thin sub-layer mined by drills along seam and hydraulic jet is regarded as a coal seam protecting other sub-layers. Even in conditions that are not suitable for protective layers, this method can effectively eliminate or reduce the danger of coal and gas outbursts and improve gas drainage and utilization with less time and lower cost. The main technological processes, parameters and related facilities for mining thin sub-layer as self-protective coal seam are introduced in the following contents.

2.1 Technological process

The main technological processes are shown as follow.

Step 1: Determining the horizon of thin sub-layer for self-protective seam.

Before mining thin sub-layer as self-protective coal seam, we need to determine the coal structure and hardness of mining area by testing and analysing samples. According to the coal structure and hardness, the horizon of thin sub-layer as self-protective coal seam is chosen. When the whole coal seam mined is soft, its upper sub-layer can be mined as the thin sub-layer for self-protection and the lower sub-layer as the protected coal seam. The horizon of thin sub-layer for self-protective seam is shown in Fig. 1. When only a sub-layer of the coal seam mined is soft, the thin sub-layer in the soft sub-layer can be mined as self-protective coal seam and other sub-layers as the protected coal seams. The horizon of thin sub-layer for self-protective seam is shown in Fig. 2.

Step 2: Determine the minimum mining thickness of thin sub-layer.

The second step is to determine the minimum mining thickness of thin sub-layer. Before mining thin sub-layer as self-protective coal seam, we should determine its minimum mining thickness. The minimum mining thickness of thin sub-layer can be determined during preliminary design by numerical simulation or using an empirical formula. After the thin sub-layer considered as a self-protective coal seam is mined, the pressure of other sub-layers of coal seam should be fully relieved and the danger of coal and gas outburst should be eliminated. The minimum mining thickness of the thin sub-layer can be estimated by

$$\frac{M_0}{M - M_0} = K_1 \varepsilon \tag{1}$$

where M_0 is the minimum mining thickness of the thin sub-layer, M is the thickness of the entire mining coal seam, ε is the critical relative expansion deformation with full pressure relief, and K_1 is the effective deformation coefficient.

Step 3: Construct the drills along seam in a coal roadway.

The third step is to construct the drills along seam in a coal roadway for thin sub-layer mining with hydraulic jet. The design of the drills along seam is shown in Fig. 3. Borehole trajectory needs to evenly distribute and remain parallel for thin sub-layer mining with hydraulic jet. Boreholes need to remain parallel to coal seam by directional drilling. The spacing between boreholes is l , and the length of boreholes is D .

Step 4: Thin sub-layer mining with drills along seam and hydraulic jet.

After finishing the drill along seam in a coal roadway, we need exit the drill pipes. Then, we need to link the mining nozzle, high-pressure steel pipe and high-pressure water supply

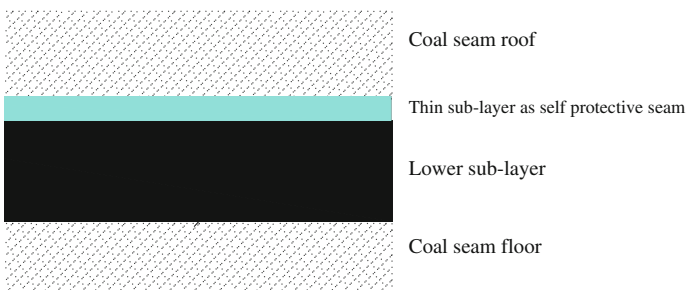


Fig. 1 Upper sub-layer as self-protection coal seam

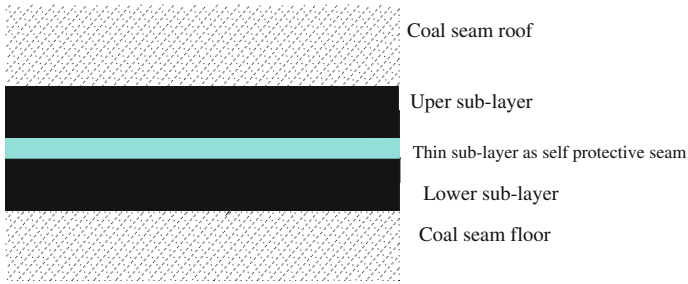


Fig. 2 Soft sub-layer as self-protective coal seam

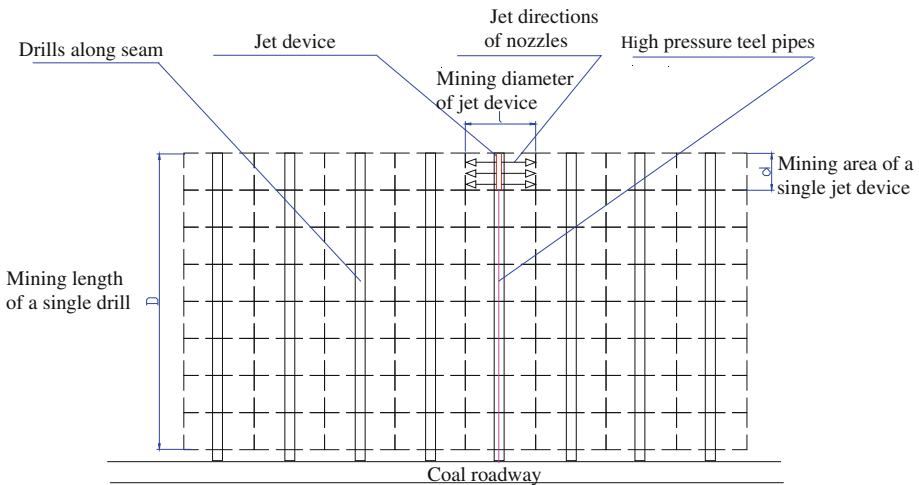


Fig. 3 Thin sub-layer mining with drills along seam and hydraulic jet

system, and place the mining nozzle in the bottom of drill and fix it by drilling rig and high-pressure steel pipe. Then, we can start to mine the thin sub-layer. When we complete the mining of thin sub-layer in a certain position of the drill, we need to move the mining nozzle outward and go on with the mining until completing the mining in the whole drill. Thin sub-layer mining with drills along seam and hydraulic jet is shown in Fig. 3.

In these figures, l signifies the mining diameter of jet device, D signifies the mining length of a single drill, l and d signify the mining area of jet device, D and l signify the mining area of a single drill, and the directions of the arrows signify the jet directions of the nozzles.

2.2 Technological parameters

The design parameters of thin sub-layer mining include the parameters for drills and hydraulic jet. The parameters for drills include the potion, number, angle, length and mining area of a single drill. The mining area of a single drill is the key parameter and is determined by the practical effective mining range of the hydraulic mining nozzles. The superimposed area of hydraulic mining should cover the entire area of the protective coal

seam. The parameters for hydraulic jet include the parameters of jet device; nozzles; and the pressure, flow and time of jet. Jet nozzles are installed in jet device. Mining area of a single jet device is determined by the number of nozzles installed in jet device and the parameters of nozzles.

Tests have shown that the hydraulic mining range of a nozzle is mainly affected by the hardness coefficient of the coal seam and the hydraulic jet pressure, flow and time. The hardness coefficient of the coal seam is the key factor in hydraulic mining: the difficulty of hydraulic mining increases as the hardness coefficient increases. For a constant coal seam hardness coefficient and a given hydraulic mining nozzle, the hydraulic mining range for a single nozzle is increased with increasing jet pressure, flow and time. The hydraulic mining range depends on the coal seam hardness, jet pressure, jet flow and jet time, as shown in equation (2):

$$l = F(P, L, f, T) \tag{2}$$

where l is the hydraulic mining range of a nozzle, P is the jet pressure, L is the jet flow, f is the hardness coefficient of the coal seam, T is the jet time and F signifies that R is a function of P , L , f and T .

The pressure, flow and time are the main hydraulic jet parameters that influence the hydraulic mining range, and those parameters should be designed on the basis of the design mining range of a nozzle and the hardness coefficient of the coal seam. At the same time, the jet pressure, flow and time should be adjusted on the basis of the actual hydraulic mining data collected during the hydraulic mining of the thin sub-layer. The design jet parameters are shown as Table 1.

2.3 Mining equipments

2.3.1 Jet device for hydraulic mining

The jet device is the key piece of equipment used in hydraulic mining of thin sub-layers. The main design parameters of jet device are the quantity, angles and positions of the nozzles installed on the jet device.

The hydraulic jet device consists of three parts: the front part for drilling, the intermediate part for nozzle installation and the rear part for connecting to the high-pressure steel pipe. The structure of a hydraulic jet device is shown in Fig. 4. Several nozzles at different positions can be installed in the intermediate part of the hydraulic jet device.

The shape of the nozzle used in hydraulic mining is a flat cuboid, and the shape of its jet is a flat cuboid. As the nozzles and jet move into the horizon of the thin sub-layer, a flat cuboid space is formed. To delay the caving time of the flat cuboid space in soft coal seam, a certain number of coal barriers need to be retained during hydraulic mining in the thin sub-layer. The range of hydraulic mining and the protective barriers are shown in Fig. 4.

Table 1 Jet parameters

Hardness coefficient of coal seam	Designed mining diameter of jet device (m)	Pressure of jet (MPa)	Flow of jet (L/min)	Time interval for jet device moving (min)
0–0.2	6	34	340	5–10
0.2–0.4	4.5	36	340	10–15
0.4–0.6	4	45	320	15–20

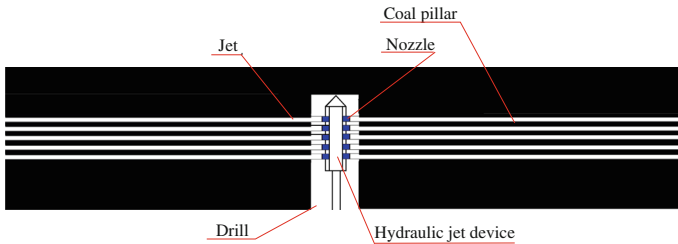


Fig. 4 Jet device for hydraulic mining

Ten nozzles are installed in the hydraulic mining bit, and the horizons of their jets are approximately parallel to the horizon of the thin sub-layer.

2.3.2 Device for preventing gas from spraying out from the cross drill

A protective device is needed to prevent a large amount of gas spraying out from the drill along seam and causing a high concentration of gas. The protective device can also be used to extract the released gas as well as to separate the coal slag, water and gas produced during the hydraulic mining of the thin sub-layer. The protective device for preventing gas spraying out is shown in Fig. 5.

2.3.3 System for thin sub-layer mining

An emulsion pump can be used to supply high-pressure water. The type of pump commonly used in coal mining is BRW400/31.5, which has a rated flow of 400 L/min and a rated pressure of 31.5 MPa. When the rated pressure of the emulsion pump is lower than the pressure needed for hydraulic mining, two emulsion pumps can be used in series. When the rated flow of the emulsion pump is lower than the flow needed for hydraulic mining, two or more emulsion pumps can be used in parallel. The hydraulic mining system is shown in Fig. 6.

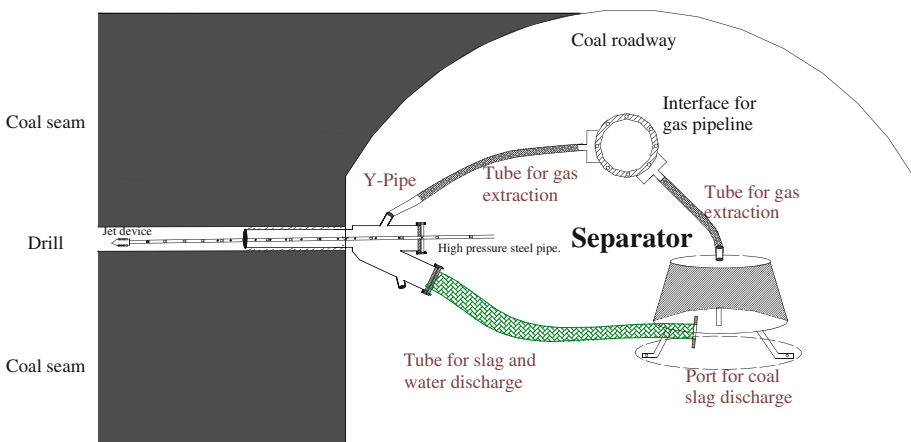


Fig. 5 Device for preventing gas spraying out and separator of coal slag, water and gas

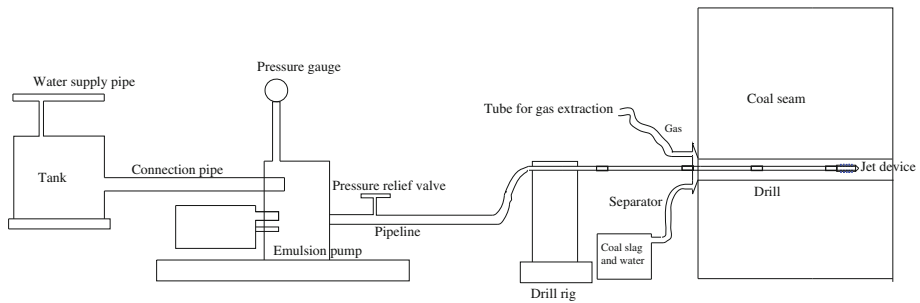


Fig. 6 System for thin sub-layer mining

2.4 Application

The underground hydraulic mining technology for thin sub-layer extracted as a protective coal seam was first applied in the Yian mine. The Yian mine is one of the Chinese coal mines that poses a danger of coal and gas outbursts, and as such, it is strictly monitored by the government. The mine is located in Henan, a province in the center of China (Fig. 7), and exhibits complex geological and mining conditions. The Yian coal field stretches 28.744 km from north to south and has a width of 6.3 km that covers an area of 28.744 km². The coal field lies between longitudes 112°09'43" E and 112°14'45" E and between latitudes 34°47'30"N and 34°51'41"N. The field produces 1.2 million tons of coal annually. There are 2 layers of completely or partially mineable coal seams, with a total thickness of 4.84 m, within the coal field. The target seam of the mine for economic production is the 2₁ coal seam, which has an average dip angle of 5° and is mined using the long wall mining method.

The 2₁ coal seam is soft, has low permeability and poses a danger of coal and gas outbursts. The hardness coefficient of 2₁ coal is 0.17–0.40, the permeability coefficient is 0.0052–0.0083 m²/MPa²·d, the gas pressure is 0.29–1.51 MPa and the gas content is 4.02–12.19 m³/t. The 2₂ coal seam lies over the 2₁ coal seam, and the average space between the coal seams is 24.69 m. The 2₂ coal seam is a partially mineable coal seam with an average thickness of 0.69 m. Because the 2₂ coal seam is the only coal seam close to the 2₁ coal seam, the 2₁ coal seam does not meet the conditions for mining protective coal seams by conventional methods, so the method of mining thin sub-layer as self-protective coal seam was applied to reduce the potential for coal and gas outbursts in the Yian mine. As the whole 2₁ coal seam is soft, we chose its upper sub-layer as thin sub-layer for self-protection and the lower sub-layer as the protected sub-layer. The working faces with a relatively small risk of coal and gas outburst in the 2₁ coal seam were chosen as the applied sites. The goal was to eliminate the threat of coal and gas outbursts and improve the gas permeability of the protected sub-layer in the 2₁ coal seam.

We determined the hydraulic mining diameter for hydraulic jet device and different jet pressures in three mining drills. Before the hydraulic mining was begun, some test drills surrounding the hydraulic mining drills were drilled. The spacing between the test drills is 0.2 m. The drills for the hydraulic mining and the drills for testing the hydraulic mining diameter are shown in Fig. 8. T1, T2, T3, T4, T5, T6, T7, T8, T9, T10, T11 and T12 are the drills for testing the hydraulic mining diameter. M1, M2 and M3 are the drills for the hydraulic mining.



Fig. 7 Location for Yian mine

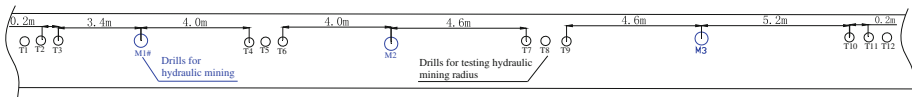


Fig. 8 Drills for testing the hydraulic mining diameter

During hydraulic mining, changes in the water flow in the test drills were monitored. Based on the change of water flow in the test drills at different spacing, the approximate range of the hydraulic mining diameter for jet device was determined. M1 is mined with a jet pressure of 30 MPa. The significant changes in the water flow in T1, T2, T3, T4 and T5 were observed and no changes in T6 were observed after the hydraulic mining in M1, which indicates that the hydraulic mining range is between T5 and T6, so the hydraulic mining diameter in M1 is between 4.2 and 4.4 m. M2 is mined with a jet pressure of 34 MPa. The significant changes in T4, T5, T6 and T7 were observed and no changes in T8 were observed after the hydraulic mining in M2, which indicates that the hydraulic mining range is between T7 and T8, so the hydraulic mining diameter in M2 is between 4.6 and 4.8 m. M3 is mined with a jet pressure of 38 MPa. The significant changes in T7, T8 and T9 were observed and no changes in T10 were observed after the hydraulic mining in M3, which indicates that the hydraulic mining range is between T7 and T10, so the hydraulic

Table 2 Hydraulic mining diameter and jet parameters

Drills for hydraulic mining	Thickness of thin sub-layer mining (m)	Hardness coefficient of the coal seam	Range of hydraulic mining diameter	Pressure of jet (MPa)	Flow of jet (L/min)	Time interval for jet device moving (min)
M1	0.2	0.19	4.2 < l < 4.4 m	30	340	10
M2	0.2	0.19	4.6 < l < 4.8 m	34	340	10
M3	0.2	0.19	5.0 < l < 5.2 m	38	340	10

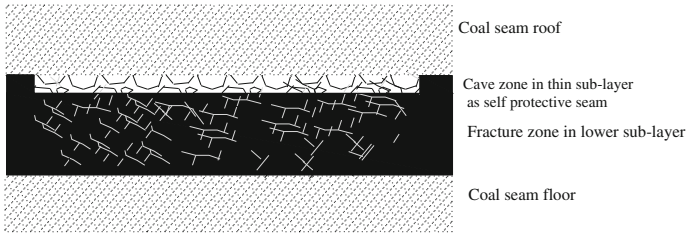
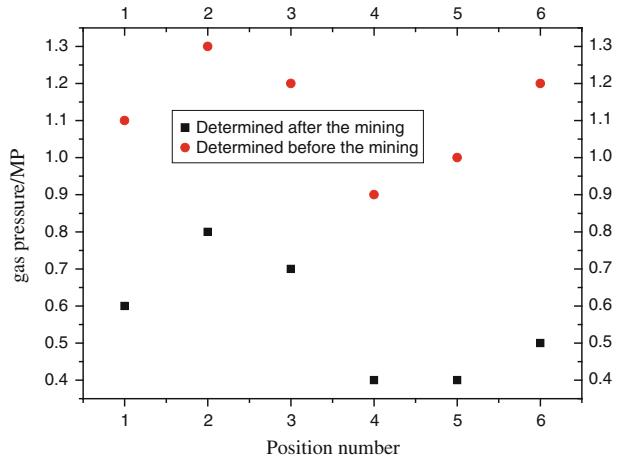


Fig. 9 Caved zone and fractured zone

Fig. 10 Determined values for gas pressure



mining diameter in M3 is between 5.0 and 5.2 m. The determined results of the hydraulic mining diameter are shown in Table 2.

3 Results and discussion

3.1 Results

Based on the range determined for the hydraulic mining diameter of a single nozzle, other mining drills were drilled, and the hydraulic mining was completed using those drills. The

Fig. 11 Determined values for gas content

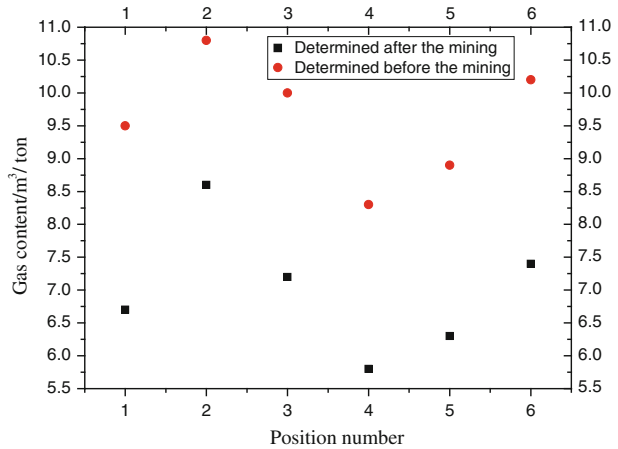
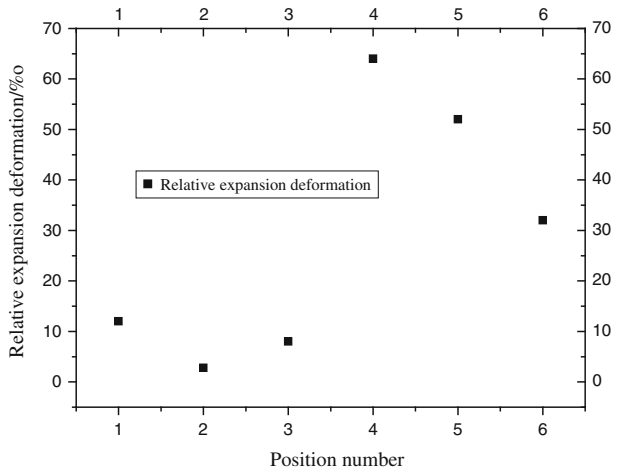


Fig. 12 Determined values for the relative expansion deformation



spacing between adjacent drills was 5 m, the jet pressure was 38 MPa, the jet flow was 340 L/min and the time interval for jet device moving was 10 min. A caved zone and a fractured zone were produced along the thin sub-layer of coal after the thin sub-layer treated as a protective seam was mined. The caved zone and fractured zone are shown in Fig. 9.

To verify that the method described in this paper eliminated the threat of coal and gas outburst, the predictors for coal and gas outburst were determined after the hydraulic mining, including gas pressure, gas content and the relative expansion deformation. Those predictors are used to predict the threat of coal and gas outburst and assess the effect of mining protective coal seam for regionally eliminate the threat of coal and gas outburst (Hargraves 1983, 1993; Lama and Bodziony 1996, 1998a; Beamish and Crosdale 1998). The critical value for gas pressure is 7.5 MPa, the critical value for gas content is 8 m³/ton and the critical value for the relative expansion deformation is 3 ‰ (State Administration of Work Safety of China 2009).

Before the mining of the thin sub-layer and after the mining of the thin sub-layer, those predictors were determined in the protected sub-layer to contrast and analysis the effect.

Those predictors were determined in six different positions in the protected sub-layer, namely in P1, P2, P3, P4, P5 and P6. Among them, P1, P2 and P3 are under the coal pillar of mining thin sub-layer, and others are under the caved zone of mining thin sub-layer. The determined results were shown as Figs. 10, 11 and 12.

3.2 Discussion

According to the values of predictors determined in different test site, we found that before the mining of the thin sub-layer, the value for gas pressure and gas content is greater than the critical value, while after the mining of the thin sub-layer, the values for gas pressure and gas content reduced greatly, and the values for gas pressure and gas content are smaller than the critical value in P1, P3, P4, P5 and P6. After the mining of the thin sub-layer, the values for the relative expansion deformation are greater than the critical value. The changes in value for gas pressure and the relative expansion deformation in P4, P5 and P6 are greater than in P1 P2 and P3.

The values for predictors determined in P1, P2, P3, P4, P5 and P6 show mining thin sub-layer as self-protective coal seam can effectively eliminate the danger of coal and gas outburst. But the coal pillars of mining thin sub-layer affected the self-protective effect in a certain extent. In order to improve the self-protective effect of mining thin sub-layer, we should reserve the pillars as little as possible. When the direct roof of thin sub-layer mined as self-protective coal seam is hard, its collapse is more difficult, and the number of pillars need to reserve is less, so we should try to choose the thin sub-layer under hard roof as self-protective seam.

4 Conclusions

Mining thin sub-layer as self-protective coal seam to reduce the danger of coal and gas outburst is a new way invented by author. This method was first applied in the Yian mine to verify its effectiveness, and gas pressure, gas content and the relative expansion deformation used to predict the threat of coal and gas outburst were determined. According to the results and discussion of application, we obtained the following conclusions:

1. Mining thin sub-layer as self-protective coal seam can effectively eliminate the danger of coal and gas outburst when mining a soft coal seam or coal seam with soft sub-layers.
2. The coal pillars retained during mining thin sub-layer affected the self-protective effect in a certain extent. In order to improve the self-protective effect of mining thin sub-layer, we should retain the pillars as little as possible.
3. This method does not demand to mine the adjacent coal seams as the protective coal seam, and it just needs to construct the drills along coal seam and mine thin sub-layer by jet to reduce the danger of coal and gas outburst. So this method needs less time and lower cost than conventional protective layer mining, and it is of great significance for mining coal seam with the danger of coal and gas outburst.

Acknowledgments The author is grateful to the Mutual Funds of Shanxi Province Coal Bed Gas (2012012010), the Dr. Funds of Henan polytechnic university (648708), Yima coal group co., LTD and the postdoctoral workstation of Shanxi jincheng anthracite mining group co., LTD for their support for this project.

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