Nat Hazards (2013) 67:763–782
DOI 10.1007/s11069-013-0602-5

ORIGINAL PAPER

Gas outburst disasters and the mining technology of key protective seam in coal seam group in the Huainan coalfield

Haifeng Wang · Yuanping Cheng · Liang Yuan

Received: 10 January 2013 / Accepted: 14 February 2013 / Published online: 23 February 2013

Abstract Coal and gas outburst disasters in coal seams are becoming more serious as coal mines extend deeper underground in China. To aid gas control in high-gas outburst coal seam group, this study performed research based on the geological conditions of the Xinzhuangzi coal mine in the Huainan coalfield. The laws of gas occurrence, the strength of the coal outburst, and the regional partition were studied. Simultaneously, we introduced the key protective seam mining technology and confirmed the mining sequence of coal seam groups. The results indicate that (1) each seam absorbs gas well, and the currently measured gas content is up to 15.0 m^3/t. (2) Although some differences about coal seams outburst intensity remain, the differences in the same group are very small. (3) The coal seam B10 was chosen as the key protective seam and was mined first; then adjacent seams were mined from bottom to top by layer within the roof of B10 and from top-to-bottom within the floor of B10 to guarantee each adjacent coal seam received the good effects of pressure-relief and increasing permeability. (4) The main methods of gas extraction in each protected seam are surface boreholes and net-like penetrating boreholes in the floor roadway, and related technical parameters were determined according to the degree of pressure-relief in coal seam. This in situ experiment indicates a method aiding the gas control problem and guaranteeing safe and highly efficient exploitation of high-gas outburst seams.

Keywords Coal seam group · Gas occurrence · Coal and gas outburst disaster · Key protective seam · Gas control

1 Introduction

With the coal mines extending deeper underground in China, the pressure of gas in coal seams increases, and the risk of coal and gas outburst disasters becomes more serious.

H. Wang · Y. Cheng (✉)
National Engineering Research Center of Coal Gas Control, China University of Mining and Technology, Xuzhou, Jiangsu 221116, China
e-mail: baizhizhuang@163.com

L. Yuan
Huainan Mining Industry(Group) Limited Liability Company, Huainan, Anhui 232046, China

China now has the world's highest risk of outburst disasters (Cheng 2010). Many gas control methods in outburst seams exist (Cervik 1979; Noack 1998; Creedy and Tilley 2003; Cheng et al. 2009), but a comparative analysis indicates that the protective seam mining technology is the most economical and effective method (Yu et al. 2004; Brandt and Sdunowski 2007; SAWS 2005, 2008). The low-gas coal seam, which is mined first, is called the protective seam; correspondingly, the coal seam in danger of an outburst danger is called the protected seam. Pressure-relief gas drainage from the protected seam (the outburst coal seam) could extract gas with high efficiency after protective seam mining. The protective seam mining technology originated in France was developed (Yu 1986) and applied widely in the first decade of this century. It provided the technical support for improving the safety of Chinese coal mines in recent years.

Protective seam mining technology involves two coal seams: the protective seam and the protected seam. Generally, the protective seam contains no potential outbursts, and the protected seam contains potential outbursts. Many studies in Chinese coalfields have focused on protective seam mining, leading to a large amount of data and achieving good effects on gas extraction (Yuan 2003; Cheng et al. 2004; Tu et al. 2007; Wang et al. 2008). The object of previous research on protective seam mining technology has, however, focused most on the one-to-one protection of protective and protected seam. Generally, we chose seam in no danger of outbursts as the protective seam, making the selection of protective seam simple. However, there are some mines featuring many coal seams. An example of this, the Huainan mine area contains more than 40 layers in the coal-bearing strata with nearly 9–10 outburst seams present in those currently mined, with small distances between each seam. Mining any one seam of the coal seam group influences the upper and lower adjacent coal seams (Liu et al. 2009; Fang 2010). Adopting the protective seam mining technique is complicated in this case because one first needs to select the seam most suitable as a protective seam to be the key protective seam, and then one proceeds to mine through analyzing the gas occurrence and the characteristics of any outburst disaster of that particular coal seam group. Coupling the mining of a key protective seam with gas pressure-relief extraction could eliminate the outburst risk in upper and lower adjacent coal seams. Moreover, the upper–lower adjacent coal seams may perform pressure-relief protection for other seams, acting as sub-protective seams, until all seams achieve pressure-relief protection.

This study focused on the geological conditions of the Xinzhuangzi coal mine in the Huainan coalfield. Our research obtained the law of gas occurrence, the coal outburst risk, the outburst features, and the regional divide of each coal seam under the conditions of the coal seam group. On this basis, we investigated key protective seam mining technology and analyzed the technical principles and selection of the key protective seam. In addition, we determined the order of mining of the coal seam group and the gas control measures of the key protective seam and pressure-relief gas extraction and their related technical parameters in the protected seam. Our results show that this method could solve the gas control problem and guarantee safe and highly efficient exploitation of a high-gas outburst coal seam group.

2 General geology

The Huainan coal mine is located in the hinterland of East China, in the north-central Anhui province near the cities of Huainan and Fuyang. The Huainan Mining Group has 13 operational mines, producing 67.19 Mt/a of raw coal in 2010, and of these mines, 12 are coal and gas outburst mines. The Xinzhuangzi mine is located west of Huainan and east of Mount Bagong, and the mine field crosses north and south of the Huai River. South of the

Huai River, a broad peneplain stands in front of the mountains, and north of the Huai River, an alluvial plain stands in the River Gorge. The mine field average along strike length is 5.40 km, and the average width of its tilt is 3.75 km, with an area of 17.79 km^2. The Xinzhuangzi mine was established in May 1947 and has experienced many extensions. In addition, its production capacity is 4.0 Mt/a. Figure 1 depicts the study area.

2.1 Coal-bearing stratum

The Huainan coal mine belongs to a sedimentary formation located in the southern margin of North China platform. The coal-bearing strata are permo-carboniferous. The Taiyuan Formation of the Upper Carboniferous has thin layers that are extraordinarily unstable and have no value for exploitation. Most of the coal-bearing strata in the mine field in this study are Permian, and the total thickness of the coal-bearing strata is 820.69 m, containing more than 40 layers. The Quaternary layers cover the Permian layers, concealing the coalfield, which is divided into five coal-bearing groups from bottom to top: A, B, C, D, and E and into seven coal-bearing sections. The primary mining activities of the Xinzhuangzi coal mine take place in three coal-bearing groups: A, B, and C and four coal-bearing sections. Four coal-bearing sections thickness reaches approximately 354.74 m and includes more than 20 coal seams, with workable seams reaching approximately 31.96 m in thickness. The primary coal mining seams include C13, B11b, B10, B8, B7a, B6, B4, A3, and A1. Figure 2 displays the histogram of coal-bearing strata. Coal Seams D and E are thin, poor, and unstable and are, therefore, not mined in the Xinzhuangzi coal mine.

Fig. 1 Map showing the study area

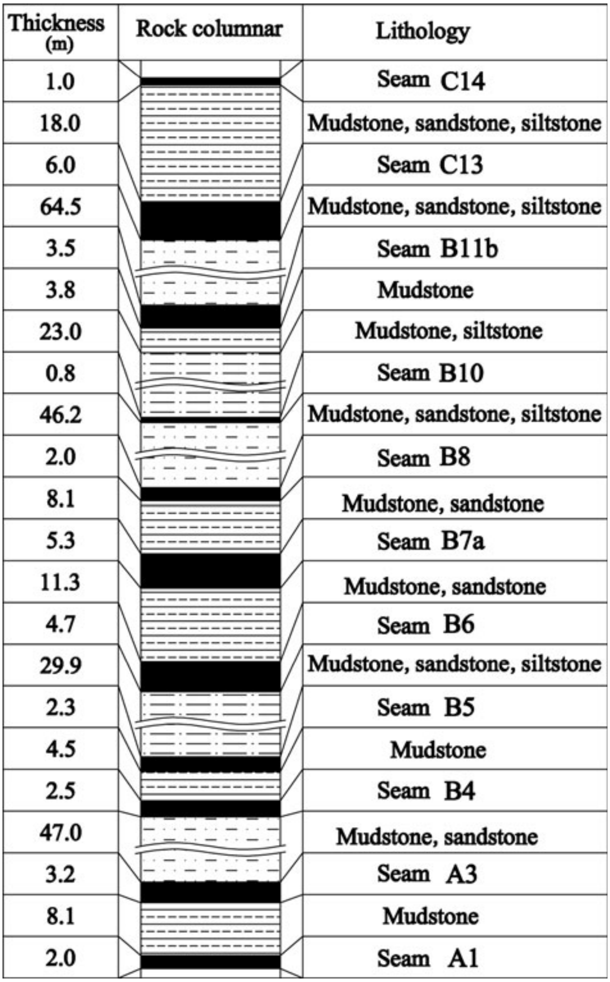

Fig. 2 Histogram of coal-bearing strata

2.2 Regional tectonics

The Huainan coalfield is located on the eastern edge of the Qinling latitudinal structural belt, surrounded by the Tanlu fault zone, the Zhoukou sag, the Bengbu-Mengcheng uplift, and the Hefei-Huoqiu sag. The Huainan coalfield is located between the Fufeng overthrust and the Shungeng Mount overthrust, a characteristic beneficial to gas preservation. Under the north–south compressive stress, the edge stratum has a strong fold, a thrust, and an overthrust, causing the stratum to slope, steep dip, upright tilt, and upright inversion. The inside plain features a mild-folded form, developing sub-first grade anticlines and synclines.

2.3 Coalfield structural features

Overall, the coal seams in this coalfield are monocline. The strike and inclination of strata are N 40° W and NE, respectively, and the range of obliquity is from 10° to 55°. The main geological tectonic feature of the coalfield is its fault structure, but some seams partially develop small-scale folds. Two fault groups control the structural form of the whole coalfield, F6–F7 and F10-5–F11-9, which belong to the II sequence large-scale fault structure. The strike of its extension is N 60°–80° W. Its inclination is SSE, and the range of obliquity is from 45° to 60°. All are dextral normal faults. Two II sequence fault structures could divide this coalfield into three geological units, including one north of the fault groups F6–F7 (north F6), one between fault groups F6–F7 and F10-5–F11-9 (between F10-5 and F6) and one south of fault group F11-9 (south F11-9). Many sequence fault structures develop in each geological unit, especially in the tectonic area between fault groups F6–F7 and F10-5–F11-9, which has a middle-sized fault every 120 m. In addition, the direction of spread on these parallel structures is NNE, and the inclination is NNW. The obliquity contrasts with the II sequence fault structure, and the III sequence fault structure consists of a bias cutting normal fault accounting for 90 % and a reverse fault accounting for 10 %. Figure 3 depicts the tectonic distribution of the mine.

3 Seam gas occurrence

3.1 Proximate analysis and test result analysis for adsorption of each seam

In the process of mining coal, we tested adsorption, performed proximate analysis on many samples from each coal seam, and obtained data, shown in Table 1. Because the spans between selected samples are greater and some differences between coal types occur at the different depths in the same coal seam, the parameter indexes for some tested seams have differences. The range values and average values of each index are, therefore, also illustrated in Table 1. From Table 1, the average value of the adsorption constant “a” of each seam is 18.5–22.3 m^3/t, and the average value of the adsorption constant “b” is 0.92–1.31 MPa^{-1}. Additionally, the wash content is 1.02–1.50 %, and the ash content is

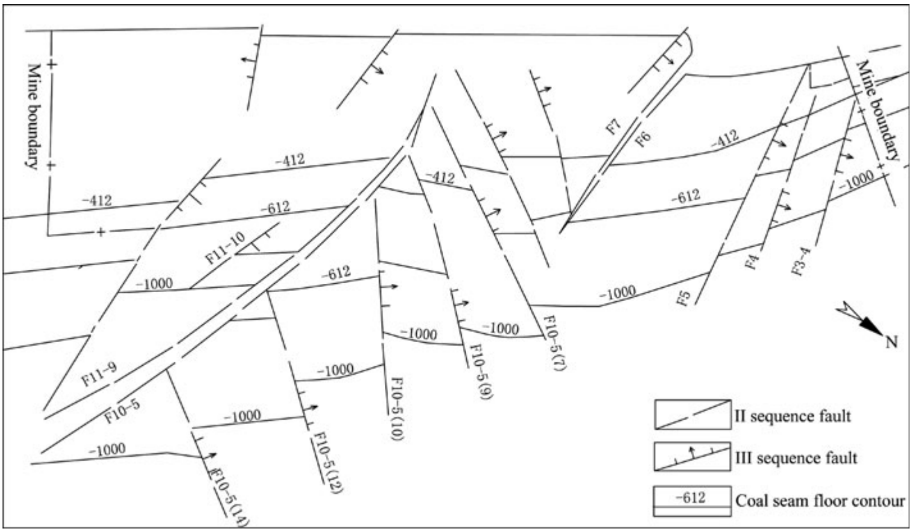

Fig. 3 Mine tectonic distribution

Table 1 Proximate analysis and test results on the adsorption of each seam

Seam	Data category	a (m^3/t)	b (MPa^{-1})	Water content (%)	Ash content (%)	Volatile (%)	Porosity volume (m^3/t)	Sample number
C13	Range	20.7–23.8	0.74–1.17	0.64–1.77	15.6–18.2	26.3–30.4	0.06–0.09	4
	Average	22.3	0.95	1.21	16.9	28.4	0.06	
B11	Range	16.1–23.5	1.05–1.66	0.81–1.86	14.2–31.2	15.7–25.1	0.03–0.06	7
	Average	19.9	1.14	1.07	23.9	21.6	0.05	
B10	Range	19.9–22.7	1.02–1.26	0.76–1.61	19.8–30.86	21.4–23.9	0.02–0.06	6
	Average	20.86	1.14	1.40	25.3	21.9	0.04	
B8	Range	15.9–24.1	0.82–1.23	1.06–1.65	14.1–27.4	22.2–24.6	0.05–0.06	4
	Average	19.1	1.04	1.38	19.2	22.9	0.06	
B7a	Range	18.1–25.9	0.78–1.35	1.07–1.61	15.5–25.3	20.9–26.9	0.02–0.06	6
	Average	21.8	0.97	1.41	20.9	23.8	0.04	
B6	Range	16.8–21.5	0.87–1.52	1.16–1.59	16.0–22.4	24.6–25.3	0.05–0.06	3
	Average	19.2	1.19	1.38	19.2	25.0	0.06	
B4	Range	16.5–20.6	0.98–1.41	1.06–1.55	13.8–31.4	20.3–26.7	0.03–0.07	9
	Average	18.5	1.25	1.29	18.8	21.9	0.05	
A3	Range	17.6–23.9	1.02–1.49	1.14–1.74	7.4–22.6	19.0–28.7	0.02–0.05	5
	Average	19.8	1.31	1.50	16.9	24.7	0.004	
A1	Range	17.8–22.8	0.84–1.03	0.64–1.53	7.5–16.1	23.4–29.4	0.05–0.07	6
	Average	19.7	0.92	1.02	12.2	26.5	0.06	

12.2–25.3 %. The volatility is 21.6–28.4 %, and the porosity volume is 0.04–0.06 m^3/t. The differences in the adsorption content "b" and the ash content of each coal seam are obvious, but the unobvious character of the other parameters indicates that each seam adsorbs gas well.

3.2 Seam gas pressure and content

Seam gas pressure and content are two important indexes that reflect the conditions of gas occurrence in the seam. Seam gas pressure is measured directly, and simultaneously, the gas pressure gradient and the value of gas pressure at each elevation of each coal seam are obtained using the safe line forecasting method (Cheng 2010). The seam gas content is measured by an indirect method. Substituting the results of proximate analysis and the test for adsorption for the gas content equation obtains the gas content at each elevation (Cheng 2010). The gas pressure and content of each geological unit at each coal seam are shown in Table 2, which also shows the maximum gas pressure and content tested in each geological unit at each seam. The gas pressure gradient was also obtained and used to acquire the gas pressure and content at the deepest part (1,000 m in depth) in each seam.

The maximum gas pressure of the mine, 5.8 MPa, was obtained at a depth of 730 m in Seam C13, and the gas content is 15.0 m^3/t. Comparing the gas pressure and content at a depth of 1,000 m in each seam, the sized order of gas pressure is as follows: C13 > B4 > B8 > B6 > A1 > B11 > B10 > A3 > B7. The sized order of gas content is as follows: C13 > B8 > B6 > B11 > B4 > A1 > A3 > B10 > B7.

Table 2 Gas pressure and content of each seam

Seam	Geological unit	Maximum gas pressure measured under mine						−1,000 m depth	
		Elevation (m)	Depth (m)	Gas pressure (MPa)	Gas content (m^3/t)	Gas pressure gradient (MPa/m)	Monitoring point number	Gas pressure (MPa)	Gas content (m^3/t)
C13	South 11-9	–	–	–	–	–	–	–	–
	Between F10-5 and F6	−730	750	5.8	15.0	0.0128	5	9.3	17.9
	North F6	−730	750	4.5	14.2	0.0091	4	7	16.3
B11	South F11-9	–	–	–	–	–	–	–	–
	Between F10-5 and F6	−612	630	2.2	11.3	0.0060	6	4.5	13.6
	North F6	−600	620	2.7	11.9	0.0039	7	4.3	13.5
B10	South F11-9	–	–	–	–	–	–	–	–
	Between F10-5 and F6	−812	831	2.8	9.1	0.0065	3	4	10.2
	North F6	−850	869	2.1	8.3	0.0074	4	3.2	9.5
B8	South F11-9	–	–	–	–	–	–	–	–
	Between F10-5 and F6	−700	719	3.8	13.0	0.0072	5	6	14.9
	North F6	−700	719	3.5	12.6	0.0054	5	5.1	14.2
B7a	South F11-9	–	–	–	–	–	–	–	–
	Between F10-5 and F6	−812	832	1.1	6.8	0.0027	3	1.6	8.1
	North F6	−700	720	0.9	6.1	0.0045	4	2.3	9.3
B6	South F11-9	–	–	–	–	–	–	–	–
	Between F10-5 and F6	−700	720	2.2	10.6	0.0067	3	4.2	13.0
	North F6	−700	720	2.9	11.6	0.0073	3	5.1	13.8
B4	South F11-9	−850	870	1.7	7.9	0.0029	4	2.1	9.7
	Between F10-5 and F6	−812	832	3.4	11.2	0.0085	5	5	12.5
	North F6	−700	720	3	10.8	0.0111	5	6.3	13.3

Table 2 continued

Seam	Geological unit	Maximum gas pressure measured under mine						−1,000 m depth	
		Elevation (m)	Depth (m)	Gas pressure (MPa)	Gas content (m^3/t)	Gas pressure gradient (MPa/m)	Monitoring point number	Gas pressure (MPa)	Gas content (m^3/t)
A3	South F11-9	−812	832	0.5	–	–	–	–	–
	Between F10-5 and F6	−812	832	1.8	8.3	0.0057	4	2.9	9.7
	North F6	−812	832	2.4	9.2	0.0072	4	3.8	10.5
A1	South F11-9	−700	720	1	6.7	0.0068	3	3	11.1
	Between F10-5 and F6	–	–	–	–	–	–	–	–
	North F6	−612	632	1.8	9.1	0.0074	5	4.7	13.0

3.3 Gas occurrence features of each seam

The regional tectonic evolution and tectonic features in mines of this area promote gas preservation, and most of the coal seam roof and floor are mudstone and sandy mudstone, which prevent the loss of gas. The gas pressure and content of each seam in this coal mine are generally higher. Site investigation and analysis depicts the gas occurrence features of each seam as follows:

(1) For a single coal seam, the gas pressure and content increase gradually with an increase in depth. Each geological unit in each coal seam differs greatly with regard to gas occurrence. The gas of South F11-9 is lower, but those levels in between F10-5 and F6 and south F6 are larger.
(2) The small-size faults in each geological unit greatly influence seam gas occurrence(Zhang et al. 2003). The small-size fault in the coal mine mainly consists of a normal fault, but the amount of gas emissions near the fault is much larger than normal during the process of mining. The seams near the normal fault in this coal mine also meet the requirements for gas occurrence and accumulation. Many coal mine gas outbursts occur near small-size normal faults, and other coal mines also exhibit similar phenomena.
(3) The gas pressure and content of each seam have certain differences, and the amount of seam gas is loosely related to the position of the seam. Although Seam C13 is located above another seam, the gas pressure and content of C13 are the largest.
(4) Due to the difference in the span of each adjacent seam, the main minable coal seam could be divided into three seam groups: A, B, and C. No obvious difference appeared in the gas occurrence between each seam in the same seam group, but in different seam groups, a difference in gas occurrence appeared. Overall, the gas of Group C is greater than B, which is greater than A.

4 Seam gas outburst danger analysis

4.1 Outburst danger of each seam

As an administrative rule, the rule of coal and gas outburst prevention (RCGOP) was promulgated and implemented by the State Administration of Work Safety in September 2009 and provides an important basis and guide for gas control in coal and gas outburst mines. Due to the RCGOP requirement of the identification of the outburst seam, we first located it based on the practical coal seam dynamic phenomenon. In other words, the seam that exhibits a dynamic phenomenon is identified as the outburst seam. Secondly, when features of dynamic phenomenon are unobvious or absent, we identify them using four indexes, including maximal gas pressure measured practically P, the damage type of the soft stratified coal seam, the initial speed of methane diffusion in coal Δp, and the coal solidity factor f. Table 3 displays the critical values of all of the indexes. If all of the indexes of a particular seam reach or exceed the critical values shown in Table 3, it is identified as an outburst seam (SAWS 2007, 2009).

In the process of mining, numerous coal samples are tested using the four indexes in each coal seam. Table 4 shows the number of tested samples and indexes. The initial speed of methane diffusion is maximal in the samples, the solidity factor is average, and the gas pressure is maximal. Based on site investigation, the damage type of each soft stratified

Table 3 Critical value of all of the indexes

Seam	Damage type	Initial speed of methane diffusion △p	Solidity factor *f*	Gas pressure (relatively) *P*(MPa)
Critical Value	III, IV, V	≥10	≤0.5	≥0.74

The damage type of coal seam has five grades. The grade I means undamaged coal, the grade II damaged coal, the grade III strongly damaged coal, the grade IV smashed coal, and the grade V powdery coal. The grades III, IV, and V could contribute to the coal and gas outburst

Table 4 Measured value of the index in each coal seam

Seam	Damage type	Initial speed of methane diffusion Δp		Solidity factor *f*		Gas pressure *P* (MPa)	
		Maximum	Sample number	Average	Sample number	Maximum	Measuring points
C13	III	15.5	15	0.43	15	5.8	9
B11	III	18.5	19	0.39	19	2.7	13
B10	III	12	6	0.47	6	2.8	7
B8	III	11	9	0.49	9	3.8	10
B7a	III	16	6	0.31	6	1.1	5
B6	III	13	10	0.45	10	2.9	6
B4	III	14	11	0.39	9	3.4	14
A3	III	14	5	0.35	5	2.4	8
A1	III	12	7	0.38	7	1.8	8

coal seam is III, and the part in the tectonic belts is IV or V. All of the seam gas pressures exceed 0.74 MPa. The initial speed of methane diffusion of each seam, Δp, exceeds 10, and the solidity factor *f* is less than 0.5, based on coal samples tested in a laboratory setting. Each seam exhibits an outburst danger and is considered a coal and gas outburst seam, according to the four indexes.

4.2 Features of outburst danger in each seam

Since the first coal and gas outburst occurred in Coal Seam B11 of Xinzhuangzi mine in October 1972 at a depth of 338 m, 27 total coal and gas outburst have happened. After the first outburst, the coal mine upgraded the coal and gas outbursts immediately. Table 5 shows the statistics of coal and gas outburst in each seam.

After a statistical analysis of these coal and gas outbursts, we outlined the following patterns:

(1) The danger and intensity of a coal seam outburst become more serious with increasing depth. In Seam C13, the first outburst occurred at a depth of 418 m, and the coal quantity of the outburst was 20 t. The coal quantity of outbursts was 80 t at a depth of 444 m and 1,114 t at a depth of 546 m.

Table 5 Statistics of coal and gas outburst dynamic phenomenon in each seam

Seam name	C13	B11	B8	B6	B4	A1
Time of beginning outburst	1983.2	1972.10	2005.2	1983.7	1974.5	2005.7
Depth of beginning outburst	−418 m	−338 m	−695 m	−174 m	−301 m	−535 m
Outburst times	6	5	2	3	10	1

(2) The danger of a coal seam outburst also becomes more serious with an increase in coal thickness. The thickest coal seam in the mine is C13, with an average thickness of 6.16 m. Four outbursts occurred in it, and the average outburst intensity was 260 t. The largest outburst in the mine occurred in Seam C13, with an outburst intensity of 1,114 t. The average thickness of Seam B11 is 3.5 m, and the total number of outbursts was 5, with an average outburst intensity of 105 t. The average thickness of A1 is 2.05 m, but it only featured one outburst with an intensity of 40 t.

(3) The geological tectonics greatly influenced outbursts. The degree of control of the small-sized fault was lower, and many outbursts occurred in the fractured part.

(4) Due to the special geostress of uncovering the cross-cut, the most serious risk of outbursts occurs while uncovering cross-cuts, and the intensity of the outbursts is greatest under these circumstances. Based on statistics, at least 5 outbursts occurred during the process of uncovering cross-cuts, and the outburst intensity was 227 t with the quantity of extrusive gas exceeding tens of thousands of cubic meters.

4.3 Results of the regional divide in each seam

According to this analysis, we conclude that Seams C13, B11, B10, B8, B7a, B6, B4, A3, and A1 are all coal and gas outburst seams that need to be divided into two regions: an outburst danger zone and non-outburst danger zone. Because each seam could be divided into three geological units, each geological unit also requires regional divisions. Table 6 depicts the results. In the non-outburst zone, face ventilation solves the gas problem by preventing the gas concentration from exceeding the limitation and thus guarantees the safety of the mining face. In the outburst zone, before a mining operation, it is necessary to take regional outburst prevention measure to eliminate the outburst danger in the mining face (SAWS 2006, 2009). Therefore, it is necessary to research the technology of gas control in coal seams.

5 Mining technology of the key protective layer

5.1 Technique principle

The main mining seams in this coal mine are seams C13, B11, B10, B8, B7a, B6, B4, A3, and A1, all of which are coal and gas outburst seams. According to the RCGOP, we must first take the regional outburst prevention measure to eliminate outburst risks in the seam before mining. Regional outburst prevention measures include using the mining technology of the key protective layer and gas pre-extraction technology (SAWS 2007, 2009). The average gas permeability coefficient in each coal seam is a low 0.001–0.01 $m^2/(MPa^2/d)$, exhibiting a poor ability to control gas using gas pre-extraction technology. The key protective seam mining technology uses pressure-relief gas extraction, which controls gas

Table 6 Results of regional divisions in each seam

Geological Unit	Regional divide	C13	B11b	B10	B7a	B8	B6	B4	A3	A1
South F11-9	None-outburst danger zone	Above −380 m	Above −200 m	–	Above −612 m	Above −612 m	Above −612 m	Above −612 m	Above −850 m	Above −612 m
	Outburst danger zone	−380 m and below	−200 m and below	–	−612 m and below	−612 m and below	−612 m and below	−612 m and below	−850 m and below	−612 m and below
Between F10-5 and F6	None-outburst danger zone	Above −365 m	Above −312 m	Above −580 m	Above −412 m	Above −412 m	Above −412 m	Above −32 m	Above −850 m	Above −412 m
	Outburst danger zone	−365 m and below	−312 m and below	−580 m and below	−412 m and below	−412 m and below	−412 m and below	−312 m and below	−672 m and below	−412 m and below
North F6	None-outburst danger zone	Above −412 m	Above −412 m	Above −612 m	Above −412 m	Above −412 m	Above −150 m	Above −200 m	Above −672 m	Above −412 m
	Outburst danger zone	−412 m and below	−412 m and below	−612 m and below	−412 m and below	−412 m and below	−150 m and below	−200 m and below	−672 m and below	−412 m and below

If one of following characteristics in coal seams appears, the face should be regarded as an outburst danger face: (1) the face in the tectonic broken belt of the outburst seam, including fault, fold, intrusive igneous rock, etc.; (2) rapid changes in seam occurrence; (3) an area of superimposing mining stress; (4) dynamic phenomena of borehole outburst in the process of exploring the mine; and (5) outburst signs on the face well (María et al. 2007; Wang et al. 2010; Yuan 2009). This coal mine operates under the condition of a coal seam group occurrence, and so the main method of gas control in an outburst seam is the key protective seam mining technology, as shown is in Fig. 4. The protective seam below the protected seam is called the lower protective seam, and that above the protected seam is called the upper protective seam.

After mining the protective seam, movement and displacement occur in the coal and rock around stope, enabling the stress and fracture fields of coal and rock to redistribute (Palchik 2003). The geostress within the range of the roof and floor in the gob area decreases, and the pressure-relief effect appears. The pressure-relief effect is the theoretical basis for the application of the protective seam mining technology. The decrease in geostress, fracture development, and seam swelling deformation of the outburst seam (protected seam) in the roof and floor greatly increases the gas permeability coefficient. The gas adsorbed within the seam is released, enabling the conditions for gas pressure-relief flow. Permeability of protected layer increases significantly after mining of the protective coal layer, and it may be up to several hundred times, and even thousands of times, such as 2,880 times in Huainan coal area. For the lower protective layer, degree of permeability increased is affected by mining thickness of protective layer, the distance and the property of rocks from protective seam to protected seam, and angle of coal seam. For the upper protective layer, factors that affect the permeability are the same except for the mining thickness of protective layer which has nothing to do with permeability.

Coupling this with the extraction of the pressure-relief gas in the protected seam using extraction projects, including a surface borehole and an underground penetrating borehole, effectively decreases gas pressure and content and improves the mechanical strength of the coal. It fully eliminates the outburst danger and transforms the high-gas outburst seam into a low-gas non-outburst seam, thereby enhancing the safety and efficacy of mining the outburst seam. Constructing the gas extraction project in the protected seam beforehand ensures that extracting the pressure-relief gas in the protected seam is effective in the process of mining the protective seam.

According to the statistics, the minimum distance between adjacent coal seams of the 7 primary mining seams is 7.4 m, and the maximum is 59.6 m. Mining each seam could produce the pressure-relief effect on the upper and lower seams. Theoretically, each seam is a protective seam, but considering the conditions of mining protective seams without destroying the neighboring seam and the difficulty of obtaining gas control in the protective seam, assuming that all seams are protective is not realistic. The first seam mined is called a key protective seam by comparison of each seam under the conditions of the

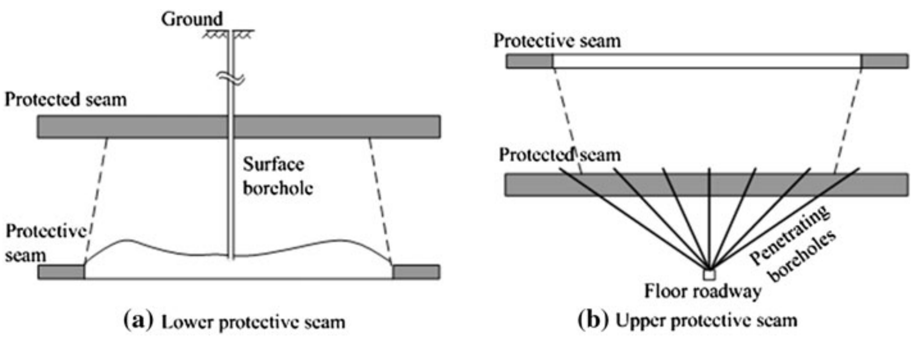

Fig. 4 Protective seam mining technology

mining seam group. In the process of mining the key protective seam and incorporating the pressure-relief extraction, the outburst danger of the protected seam in the roof and floor could be eliminated. After this, the protected seam with the eliminated outburst danger would be mined as a protective seam for the roof and floor outburst seams. After eliminating the outburst danger, the protected seam becomes a protective seam to protect other seams from outburst danger, and so on, until all of the coal seams are mined. This is the key protective seam mining technology used to mine a seam group. The choice of the key protective seam is a crucial factor for the successful application of this technology.

5.2 Choice of the key protective seam

After considering many aspects, including outburst intensity, recoverable situation, potential destruction of the roof seam, the safety of mining coal seams, and the effect of the pressure-relief, we chose Seam B10 as the key protective seam in the coal seam group to be mined first. There are some advantages of choosing Seam B10 as the key protective seam. (1) Although Seam B10 is an outburst seam, its outburst intensity is low and controlling gas in this seam is easier. (2) Seam B10 is thinner, with an average of 0.9 m, and its gas reserves are small. (3) The spatial position of Seam B10 is more reasonable, with distances from Seam B11 at 31.6 m and Seam B8 at 41 m; the mining of B10 will not destroy the mining conditions of a roof seam and will achieve a good pressure-relief effect for the roof and floor seam. (4) Seam B10 is a local non-mining thin seam, but its roof and floor are relatively soft, each consisting of silty mudstone and argillaceous siltstone. With fully mechanized units cutting the roof and floor directly, it forms a face of certain mining height. Table 7 outlines the reasons that other seams cannot serve as the key protective seam.

5.3 Mining order of the coal seams

To perform a comparative analysis of each seam, Seam B10 was mined first as the key protective seam. The upper protected seam B11 and the lower protected seam B8 obtained

Table 7 Reasons that other seams cannot be the key protective seam

Seam	Analysis of reasons
C13	High-outburst intensity, thick seam with 6 outbursts. Gas control is difficult and the position is not suitable to be a protective seam
B11	High-outburst intensity with 5 outbursts. Gas control is difficult
B8	Middle-outburst intensity with 2 outbursts. It is near Seam B7a and it is difficult to control gas gushing from its neighboring seam, which causes the gas density during workings exceed the limitation more easily
B7a	Mining Seam B7a will destroy the mining condition of overlying Seam B8 and a lot of gas from neighboring Seam B6 swarm into face, which causes the gas density during workings exceed the limitation more easily
B6	Middle-outburst intensity with 3 outbursts. Mining Seam B6 will destroy the mining condition of overlying Seam B7a
B4	High-outburst intensity with 10 outbursts. Gas control is difficult
A3	Local mining seam and its mining index being 0.50, which cannot be as key protective seam in whole-coal mine
A1	Threatened by limestone water on the floor and requires detecting and draining water, with associated long preparation time and high costs

pressure-relief and an increased permeability effect. Coupled with the pressure-relief gas extraction technology in the protected seam, Seams B11 and B8 became low-gas non-outburst seams from high-gas outburst seams. Above Seam B11 lies Seam C13, and by making the non-outburst seam B11 a sub-protective seam to control gas in C13, Seam C13 achieved pressure-relief and the increased permeability effect, eliminated its outburst danger. More layers were below Seam B8 and to eliminate the outburst danger of each seam, mining by layer from top-to-bottom was necessary. The upper seam served as the protective seam for each successive lower seam. Mining the upper seam enabled the lower seam to eliminate the outburst danger.

After eliminating the outburst danger of Seam B8 as a sub1-protective seam, it protects the next lower seam B7a as a sub2-protective seam. Then, Seam B7a protects the next lower seam B6 as a sub3-protective seam, Seam B6 protects the next lower seam B4 as a sub4-protective seam, and so on. All seams eliminate the outburst danger by using protective seam mining technology. Figure 5 displays the mining order of seams and the corresponding relation between the protective seam and the protected seam.

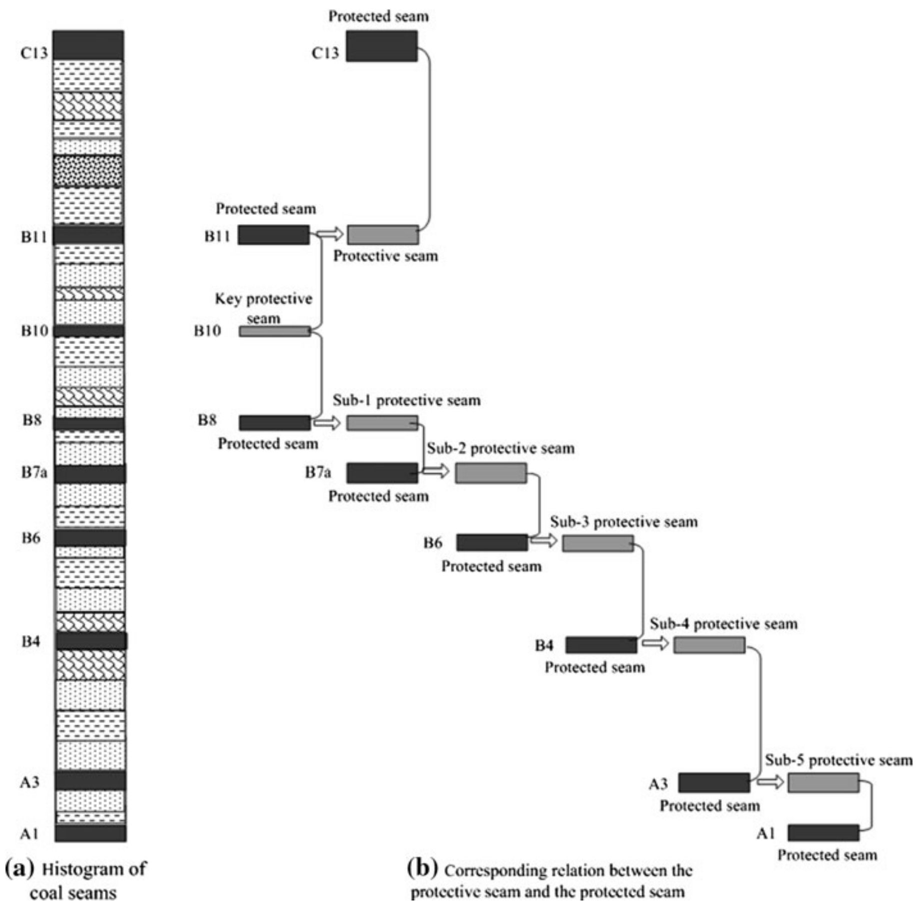

Fig. 5 Mining order of seams and the corresponding relation between the protective seam and the protected seam

Due to the top-to-bottom mining order and the small span between layers, the lower coal seams obtain the pressure-relief action of multiple mining activities. Taking seam B4 as an example, Seam B6 corresponds to the protective seam of B4, but the mining of B8 and B7a also haas certain pressure-relief effects on Seam B4. The effects of pressure-relief and increasing permeability for Seam B4 increase with the pressure-relief action of the multiple mining activities (Yuan 2003, 2009).

5.4 Gas control of key protective seam

We chose Seam B10 as the key protective seam, but Seam B10 also had a specific outburst danger that needed to be eliminated by taking a regional measure before mining. According to analysis factors, including the outburst danger and coal geology, we adopted a penetrating borehole and an along-bed borehole for gas pre-extraction to eliminate the outburst danger of Seam B10.

Penetrating boreholes were drilled into the B10 coal seam from the rock roadway, located in the floor of Seam B10. The span of the penetrating borehole was 5 m, and the sheltered range of the borehole was at least 15 m outside of the contour lines on two sides of coal roadway. After eliminating the outburst danger following months of gas pre-extraction, we drilled an intake roadway, a return roadway, and an open-off cut to form a negative-pressure ventilation system. We then constructed a dip along-bed borehole from the intake roadway and the return roadway, and the span of borehole was 3–5 m to guarantee that the along-bed borehole covered the whole-coal body in the face without leaving blank strips. The outburst danger in the whole-coal body in the face was eliminated by months of gas extraction, and the key protective seam remained a safe and highly efficient mining operation.

5.5 Pressure-relief gas extraction methods and the related technical parameters for each protected seam

Because mining the protective seam produces time-sensitive effects on the protected seam in the form of the pressure-relief and the increased permeability effect, it is necessary to extract the pressure-relief gas of a protected seam in a timely manner. On the one hand, this can effectively decrease the gas content and pressure in the coal seam and fully eliminate the outburst danger present there. On the other hand, extracting gas from a protected seam can effectively control the pressure-relief gas of the protected seam before it rushes into the face of the protective seam and decreases the gas density of the protective seam face to ensure mining safety of the protective seam face.

In the present application, the main method of gas extraction in each protected seam is surface boreholes and net-like penetrating boreholes in the floor roadway (Cheng et al. 2004; Liang 2007; Yuan 2009; Cheng 2010; Sang et al. 2010).The two methods obtain good pressure-relief gas extraction effects as shown in Fig. 4. Using the surface borehole extraction methods requires the ground to have borehole conditions, this cannot be used in mining under villages and bodies of water, and when mining the upper protective seam, the lower protected seam also cannot use this method. The gas extraction of net-like penetrating boreholes in the floor roadway is wider, allowing more general use. This method first requires the construction of a floor rock roadway along the strike below the protected seam. The construction of the penetrating boreholes within floor rock roadway is then grouped in a grid to distribute the boreholes in the seams. The length of penetrating roof is at least 0.5 m, and the span of the boreholes occur in the middle-thick face in the seam.

Table 8 Pressure-relief gas extraction methods and the related technical parameters of each protected seam

Seam	Gas extraction method	Parameters design	Mining type	Remarks
C13	Surface boreholes	The span of surface boreholes along strike of mining face is 250–350 m. It only needs one surface borehole along the inclination, which in the range of 1/2–1/3 upper inclination	Lower protective seam	Beyond the influential range of the Huai River
	Net-like penetrating boreholes in floor rock roadway	The floor rock roadway is located in the floor stratum of Seam C13, and the section of floor rock roadway is more than 9 m^2. The span between the floor rock roadway and Seam C13 is 15–20 m. The span of boreholes is 30–40 m, and the diameter of boreholes is at least 90 mm		
B11	Surface boreholes	The span of surface boreholes along strike of mining face is 200–250 m. It only needs one surface borehole along the inclination, which in the range of 1/2–1/3 upper inclination	Lower protective seam	Beyond the influential range of Huai River
	Net-like penetrating boreholes in floor rock roadway	The floor rock roadway is located in the floor stratum of Seam B11, and the section of floor rock roadway is more than 9 m^2. The span between the floor rock roadway and coal seam is 15–20 m. The span of boreholes is 20–30 m, and the diameter of boreholes is at least 90 mm		
B8 B7a B6	Net-like penetrating boreholes in floor rock roadway	The floor rock roadway is located in the floor stratum of Seam B6, and the section of floor rock roadway is more than 9 m^2. The span between the floor rock roadway and Seam B6 is 15–20 m and the penetrating boreholes penetrate three seams: B6, B7a, B8. The span of boreholes in Seam B8 is 20–30 m, and the diameter of boreholes is at least 90 mm	Upper protective seam Upper protective seam Upper protective seam	The span with the upper seam is too small and it cannot meet the conditions of constructing floor rock roadway
B4	Net-like penetrating boreholes in floor rock roadway	The floor rock roadway is located in the floor stratum of Seam B4, and the section of floor rock roadway is more than 9 m^2. The span between the floor rock roadway and Seam B4 is 15–20 m. The span of boreholes is 15–20 m, and the diameter of boreholes is at least 90 mm	Upper protective seam	
A3 A1	Net-like penetrating boreholes in floor rock roadway	The floor rock roadway is located in the floor stratum of Seam A1, and the section of floor rock roadway is more than 9 m^2. The span between the floor rock roadway and Seam A1 is 15–20 m. The span of boreholes in Seam A3 is 15–20 m, and the diameter of boreholes is at least 90 mm	Upper protective seam Upper protective seam	Since the span of layers is smaller, the floor of Seam A3 cannot construct floor rock roadway

Table 9 Summary of investigating results on pressure-relief and the increased permeability effect in each protected seam

Protective seam	Protected seam	Results of investigating effect
B10	B11	The quantity of gas extraction in a single borehole increases to about 1 m^3/min and the gas content of B11 drops to 3.3 m^3/t from 15 m^3/t; The maximum effect inspection index S_{max} during the mining of Seam B11 is 3.2 kg/m, and the maximum of K_1 is 0.17 mL (g min$^{0.5}$).The gas density of air return in the coal mining face is controlled below 0.6 %, and the average of daily output is 1,273 t
	B8	The gas content of B8 drops to 5.7 m^3/t from 14 m^3/t; The maximum effect inspection index S_{max} during the mining of Seam B8 is 3.2 kg/m and the maximum of K_1 is 0.23 mL (g min$^{0.5}$). The gas density of air return in the coal mining face is controlled below 0.65 %, and the average of daily output is 1,573 t
B11	C13	The gas pressure of C13 drops to 0.5 MPa from 4.4 MPa and its gas content drops to 5 m^3/t from 13 m^3/t. The gas permeability coefficient in coal seam improves to 32.69 m^2/(MPa^2 d), and relative swelling deformation is 26.33 ‰
B8	B7a	The gas pressure of C13 drops to 0.1 MPa from 1.7 MPa, and its span of layers is only 7.4 m, and could fully eliminate outburst danger
B7a	B6	The gas permeability coefficient in Seam B6 increases by 570 times and quantity of gas extraction in boreholes increases by 40 times. The gas pressure drops 0.2 MPa from 3.6 MPa. The effect inspection index S_{max} during roadway excavation are all below 4 kg/m and the K_1 are all below 0.23 mL (g min$^{0.5}$)
B6	B4	The relative swelling deformation in Seam B4 is 27.1 ‰ and its gas permeability coefficient in coal seam increases by 500 times. The quantity of gas extraction in boreholes increases by 30 times and the gas pressure drops 0.2 MPa from 3.6 MPa
B4	A3	The span of the two seams is 59.6 m, a large distance, and this seam needs further investigation
A3	A1	The span of two seams is only 7.7 m and could fully eliminate the outburst danger in Seam A1

Table 8 displays the pressure-relief gas extraction method in each protected seam and its related technical parameters. From Table 8, different seams need to use different methods of gas extraction, and their related technical parameters also differ.

5.6 Effect of mining the protective seam

After performing the experiment of mining the protective seam in recent years, each mined seam was investigated systematically. Table 9 displays these results, and each seam exhibits effective pressure-relief and an increased permeability effect. Coupling with pressure-relief gas extraction in the protected seam, it can transform the high-gas outburst seam into a low-gas non-outburst seam and allow the safe and rapid excavation on the coal roadway and the efficient recovery of the coal mining face. The comprehensive mechanized mining and the management method of all roof collapsing have been applied. The effects of Seam A3, as protected by Seam B4, are uncertain because the pressure-relief effects were not investigated.

6 Safe production in the Xinzhuangzi coal mine

With the extensive application of the key protective seam mining technology, coupled with gas extraction technology in mining, the quantity of gas extraction in the Xinzhuangzi coal mine increased significantly. In addition, the security situation improved, and the death rate per million tons decreased. No coal and gas outburst have occurred in the most recent 4 years. The coal output of the coal mine was 3.367 Mt in 2010, and the quantity of gas extraction was 34.2 Mm^3. Moreover, gas density exceeded the limitation once, and the death rate per million tons was 0.00297. This coal mine achieves the goal of safe production.

7 Conclusions

(1) After field measurement and analysis, the laws of gas occurrence in each main coal seam were obtained. The maximum gas pressure in the present measurement was 5.8 MPa, and the gas content was 15.0 m^3/t. The gas pressure and content of coal seam increased gradually with an increase in depth. Small faults could have a great influence on gas occurrence as well. In addition, gas in Group C was greater than those in Group B and even greater than those of Group A.

(2) All of the seams have outburst danger, but the outburst intensities differ among them. Our analysis shows that the outburst intensity increased with an increase in depth and thickness. The situation of geostress in geological tectonics and the uncovering of cross-cuts contribute to causing outbursts.

(3) The key protective seam mining technology and its principle technique were described. Seam B10 was chosen as the key protective seam, and the mining order of coal seams was determined. The pressure-relief gas extraction methods and the related technical parameters of each protected seam were determined. The protective seam adopted penetrating borehole and along-bed borehole methods for gas pre-extraction, and the primary methods of gas extraction in each protected seam were surface boreholes and net-like penetrating boreholes in the floor roadway. In situ research showed that this method aided the problem of gas control and guaranteed safe and highly efficient exploitation for a high-gas outburst seam group.

Acknowledgments The authors are grateful to senior engineers Bai, F.S, Zhong, H.R and Jiao, X.J of the Huainan mining industry (group) Co., Ltd. for their assistance with first-hand information of the coalfield. Funding for this research was provided by National Basic Research Program of China (973 Program, No. 2011CB201204) and Program for New Century Excellent Talents in University.

References

Brandt J, Sdunowski R (2007) Gas drainage in high efficiency workings in German Coal mines. In: Proceeding of 2007' China (Huainan) international symposium on coal gas control technology. Xu zhou, China university of mining and technology press 22–29

Cervik J (1979) Methane control on longwalls—European and U.S. practices. Longwall-Shortwall Mining, Art. Society of Mining Engineers of American Institute of Mining, Metallurgical, and Petroleum Engineers, New York 9:75–80

Cheng YP (2010) Mine gas hazard control theory and engineering application. China university of mining and technology press, Xuzhou

Cheng YP, Fu JH, Yu QX (2009) Development of gas extraction technology in coal mines of China. J Min Saf Eng 26:127–139

Cheng YP, Yu QX, Yuan L (2004) Experimental research of safe and high—efficient exploitation of coal and pressure relief gasin long distance. J China Univ Min Technol 33:132–136

Creedy D, Tilley H (2003) Coal-bed methane extraction and utilization. J Power Energy 217:19–25

Fang LC (2010) Gas pressure releasing and drainage theory and application technology in Huainan mining area. Coal Sci Technol 79:97–112

Liang YP (2007) Practice of methane drainage by surface well drilling in Huainan mining area. J Min Saf Eng 24:409–413

Liu DM, Yao YB, Tang DZ (2009) Coal reservoir characteristics and coalbed methane resource assessment in Huainan and Huaibei coalfields, Southern North China. Int J Coal Geol 79:97–112

María B, Díaz A, González NC (2007) Control and prevention of gas outbursts in coal mines, Riosa–Olloniego coalfield, Spain. Int J Coal Geol 69:253–266

Noack K (1998) Control of gas emissions in underground coal mines. Int J Coal Geol 35:57–83

Palchik V (2003) Formation of fractured zones in overburden due to longwall mining. Environ Geol 44:28–38

Sang SH, Xu HJ, Fang LC (2010) Stress relief coalbed methane drainage by surface vertical wells in China. Int J Coal Geol 82:196–203

State administration of work safety (2005) 50 gas treatment experiences. China coal industry publishing house, Beijing

State administration of work safety (2006) Basic indicators for mine gas drainage, AQ1026–2006. China coal industry publishing house, Beijing

State administration of work safety (2007) Coal mine safety regulations. China coal industry publishing house, Beijing

State administration of work safety (2008) Protective mining technical specifications, AQ 1050–2008. China coal industry publishing house, Beijing

State administration of work safety (2009) Provisions of the prevention of coal and gas. China coal industry publishing house, Beijing

Tu M, Huang NB, Liu BA (2007) Researchon pressure—relief effect of overlying coal rock body using far distance lower protective seam exploitation method. J Min Saf Eng 24:418–426

Wang L, Cheng YP, Li FR (2008) Fracture evolution and pressure relief gas drainage from distant protected coal seams under an extremely thick key stratum. Min Sci Technol (2): 182–186

Wang HF, Cheng YP, Wu DM, Liu HY (2010) Gas emission and parameter optimization of gas extraction in mining face of short distance protective seam. J China Coal Soc 35:590–594

Yu QX, Cheng YP, Jiang CL, Zhou SN (2004) Principles and applications of exploitation of coal and pressure relief gas in thick and high-gas seams. J China Univ Min Technol 33:127–131

Yu BF (1986) Mining liberation layer's understanding and practice. The coal industry press, Beijing

Yuan L (2003) Research on gas drainage technology for seam group with complicated and difficult conditions. Coal Sci Technol 31:1–4

Yuan L (2009) Theory of pressure relieved integrated coal production and gas extraction. J China Coal Soc 34:1–8

Zhang GC, Xiong MF, Guo WX, Tang YY (2003) Huainan diggings compartmentalized small structure of coal and gas outburst of control function. J Jiao zuo Inst Technol (Nat Sci) 22:329–333