CrossMark

Development and application of an efficient gas extraction model for low-rank high-gas coal beds

Baiquan Lin[1,2] · He Li[1,2] · Desheng Yuan[1,2,3] · Ziwen Li[1,2]

Abstract To promote gas extraction in low-rank high-gas coal beds, the pore structure characteristics of the coal and their effect on gas desorption were studied. The results show that micropores are relatively rare in low-rank coal; mesopores are usually semi-open and inkpot-shaped whereas macropores are usually slit-shaped. Gas desorption is relatively easy at high-pressure stages, whereas it is difficult at low-pressure stages because of the 'bottleneck effect' of the semi-open inkpot-shaped mesopores. A 'two-three-two' gas extraction model was established following experimental analysis and engineering practice applied in the Binchang mining area. In this model, gas extraction is divided into three periods: a planning period, a transitional period and a production period. In each period, surface extraction and underground extraction are performed simultaneously, and pressure-relief extraction and conventional extraction are coupled to each other. After applying this model, the gas extraction rate rose to 78.8 %.

Keywords Low-rank coal · Pore structure · Gas extraction · Inkpot-shaped pore

1 Introduction

Underground gas extraction has been a conventional method to guarantee safe production in high-gas coal beds in China (Lin 2010). Since the 1980s, coalbed methane extraction through surface wells has been popular in China, achieving the simultaneous extraction of coal and gas (Li et al. 2014). At present, the exploitation of coalbed methane in China is concentrated in medium- and high-rank coalfields. Research in low-rank coalbed methane extraction is immature (Qiao 2009). Owing to advances in low-rank methane exploitation in the Powder River Basin, Raton Basin and Alberta Basin, the economic value of low-rank coalbed methane increased (Fu et al. 2006; Sun et al. 2009; Ye et al. 2009). In China, coalbed methane resources in low-rank coalfields account for 47 % of the gross amount (Liu and Gao 2014). A typical low-rank coal bed is characterized by multiple layers, large thicknesses, high permeability and low gas content. The huge reserve of coal can be offset by its poor gas content, and thus coalbed methane from low-rank coal has good prospects for future development (Han 1980).

Coalbed methane is a natural gas resource adsorbed within a coal reservoir. Its production must involve a depressurization desorption stage (Qin et al. 2012). In addition, the geological carrier of coalbed methane, coal itself, is an important source of energy. How to break the limitations of the two independent industries involved with surface and underground gas extraction, and how to organically coordinate the safety of coal mining and the high-efficiency exploitation of coalbed methane, are problems of efficient gas extraction in high-gas coal beds.

The Binchang Jurassic coalfield area is located on the southwest margin of the Erdos basin. It is one of the most

✉ Baiquan Lin
  lbq21405@126.com

1 The State Key Laboratory of Coal Resources and Mine Safety, China University of Mining and Technology, Xuzhou 221008, China

2 Faculty of Safety Engineering, China University of Mining and Technology, Xuzhou 221008, China

3 Shaanxi Binchang Mining Group Co., Ltd., Xianyang 721000, China

promising low-rank mining areas in China (Liu et al. 2011; Tian et al. 2012). Coal and gas reserves in the Binchang mining area reach 5.03×10^9 tons and 9.75×10^9 m^3, respectively. However, as the mining area extends, gas emissions have become a growing problem that seriously restricts coal production. Therefore, coalbed methane must be efficiently extracted. In this paper, the pore structure characteristic of the Jurassic low-rank coal in the Binchang mining area and its effect on gas desorption were studied by means of maceral experiments, vitrinite reflectance experiments, liquid nitrogen and carbon dioxide adsorption experiments and mercury injection experiments. A 'two-three-two' gas extraction model has been proposed by summarizing experimental analysis and engineering practices.

2 Microstructural characteristics of Jurassic low-rank coal

2.1 Petrographic characteristics of Jurassic low-rank coal

The microscopic petrographic properties of coal are key parameters that characterize its metamorphic grade. Differences in coal maceral determine the pore size and distribution. Additionally, it also affects the adsorption and desorption of gas (Duan et al. 2009a, b). Six coal samples collected from different coal mines were selected for this experiment. Their maceral and vitrinite reflectance analyses are listed in Table 1.

As listed in Table 1, the vitrinite reflectance of coal samples of the Dafosi Coal Mine and Yuanzhuang Coal Mine is 0.76 and 0.89, respectively, which means the samples are from low-rank coals. The vitrinite reflectance of samples from the Guqiao Coal Mine is 2.06, thus the samples are high-rank coals. The rest of the samples are medium-rank coals. It has been indicated (Qin and Ye 1999) that more vitrinite in coal corresponds to a better adsorption capacity of gas because the vitrinite contains significant numbers of micropores that can provide huge specific surface areas for gas absorption. The vitrinite content of coal samples from the Dafosi Coal Mine is 42.67 %, much lower than that of the medium- and high-rank coal. Thus, the gas adsorption capacity of the low-rank coal is weak.

2.2 Pore structure characteristics of Jurassic low-rank coal

The gas adsorption capacity of coal is closely related to its specific surface area, and the specific surface area is dominated by its pore structure characteristics (Li et al. 2014). To assess the pore structure characteristics of Jurassic low-rank coal, gas adsorption experiments and mercury injection experiments were conducted.

Coal samples (0.2–0.25 mm in size) and an ASAP-2000 absorption instrument were selected to conduct low-temperature liquid nitrogen adsorption experiments that aimed to investigate the distribution of micropores and mesopores. The testing temperature was 77 K and the relative pressure was 0.050 to 0.995. As the diffusion of nitrogen

**Table 1** Results of the maceral and vitrinite reflectance experiments

Coal samples	Buried depth (m)	Vitrinite (%)	Inertinite (%)	Exinite (%)	Minerals (%)	$R_{o,max}$ (%)	Coal rank	Metamorphic grade
Dafosi	475	42.67	55.68	0	1.65	0.76	Bitumite C	Low
Yuanzhuang	490	63.68	34.29	0	2.03	0.89	Bitumite C	Low
Xinyu	258	77.10	22.13	0	0.77	1.36	Bitumite B	Medium
Pingdingshan No. 4 coal	800	80.21	11.68	6.93	1.18	1.83	Bitumite A	Medium
Pingdingshan No. 8 coal	720	82.96	9.57	6.07	1.40	1.90	Bitumite A	Medium
Guqiao	956	86.80	10.67	0	2.53	2.06	Anthracite C	High

Table 2 Results of low-temperature nitrogen adsorption experiments

Coal samples	Total surface area (m^2/g)	Mean pore size (nm)	Pore volume ($\times 10^{-3}$ mL/g)			
			Total	Micropore	Mesopore	Macropore
Dafosi	4.65	11.40	8.34	0.51	4.68	3.05
Xinyu	1.62	10.33	2.35	0.12	1.36	0.87
Pingdingshan No.8	4.46	5.75	7.92	0.38	3.96	3.58
Guqiao	3.32	4.70	6.42	0.39	3.54	2.49

Table 3 Results of the CO_2 adsorption experiments

Coal samples	Volume ($\times 10^{-3}$ mL/g)	Superficial area (m²/g)	Mean pore size (nm)
Dafosi	2.39	21.84	0.60
Xinyu	2.65	26.07	0.84
Pingdingshan No. 8	3.18	39.30	0.55
Guqiao	3.46	41.06	0.79
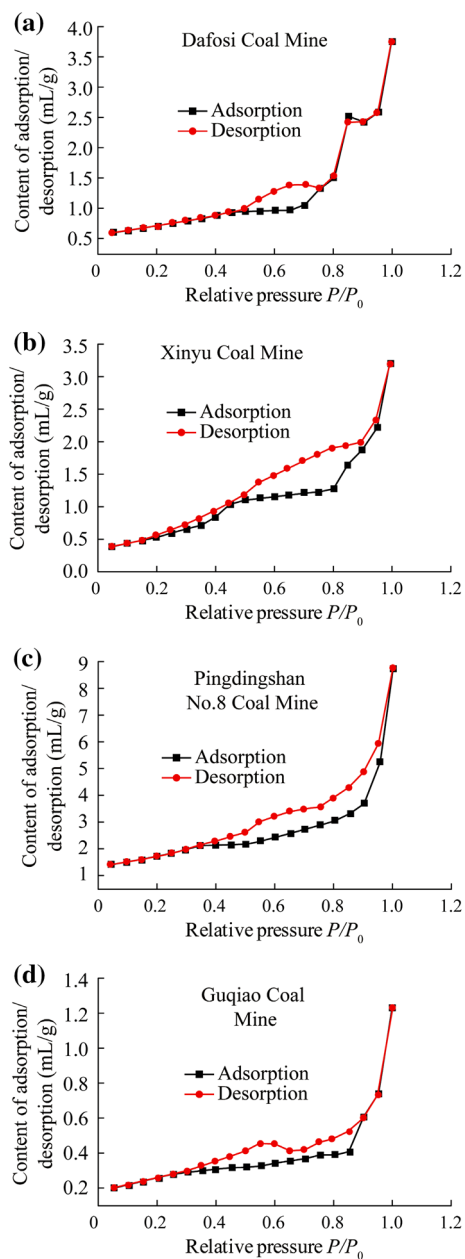
Fig. 1 Nitrogen adsorption/desorption curves

molecules in micropores under low temperature conditions is slow, results from micropore distributions are not accurate. Thus, the CO_2 adsorption experiments were conducted as a supplement to study the distribution of micropores. In the CO_2 adsorption experiments, the AUTOSORB-1 absorption instrument ran at 273 K. The results of the gas adsorption experiments are illustrated in Tables 2 and 3, and the liquid nitrogen adsorption and desorption curves are presented in Fig. 1.

Table 2 indicates that the pore volume, and especially the mesopore volume, of Jurassic low-rank coal is relatively large, and can thereby provide broad spaces for gas adsorption. However, the surface area of micropores in the Jurassic low-rank coal is relatively small, which impedes gas adsorption in low-pressure stages.

Figure 1 illustrates that the gas adsorption of Jurassic low-rank coal increases slowly under low pressure. Conversely as the pressure increases ($P/P_0 > 0.5$), an adsorption hysteresis loop appears within all samples. The appearance of the adsorption hysteresis loop mainly depends on the capillary condensation that occurs on the solid surface. The adsorption hysteresis loops of different coal samples vary considerably, indicating different pore structure characteristic effects on gas adsorption (Jiang et al. 2011). According to the shape of pores, the adsorption hysteresis loop can be divided into four categories (Kondo et al. 2006). As shown in Fig. 1, the adsorption hysteresis loop for Jurassic low-rank coal emerges under pressures of 0.5–0.8 and gradually disappears as the pressure increases. This phenomenon confirms that mesopores in low-rank coal samples usually have semi-open inkpot-shapes and macropores are usually slit-shaped. Curves for medium- and high-rank coal samples indicate that the samples contain numerous wedge-shaped and slit-shaped pores, which contribute greatly to gas desorption.

To assess the distribution of macropores, mercury injection experiments were conducted to obtain the pore size distribution, specific surface area, permeability and porosity of the coal. The experimental results are shown in Table 4, and the pore size distribution is shown in Fig. 2.

Figure 2 shows that the pore size of Jurassic low-rank coal is characterized by a bimodal distribution of mesopores and macropores. The peak pore size of the mesopores and macropores is 10 nm and 70 nm, respectively. In contrast, the pore size of medium- and high-rank coal shows a unimodal distribution with smaller magnitude. The mercury injection experiments indicate that the pore volume and specific surface area reach 0.1194 mL/g and

Table 4 Results of the mercury injection experiments

Coal samples	Dafosi	Pingdingshan No. 8 coal	Guqiao	Xinyu
Pore volume (mL/g)	0.1194	0.0237	0.0342	0.0435
Specific surface area (m²/g)	42.317	12.668	19.178	20.205
Mean pore size (nm)	11.3	7.5	7.1	8.6
Apparent density (g/mL)	1.1264	1.3206	1.2008	1.1752
Skeletal density (g/mL)	1.3014	1.3633	1.2521	1.2386
Porosity (%)	13.4486	3.1340	4.1017	5.1173
Permeability (mD)	10.3368	2.9158	5.8122	7.6307
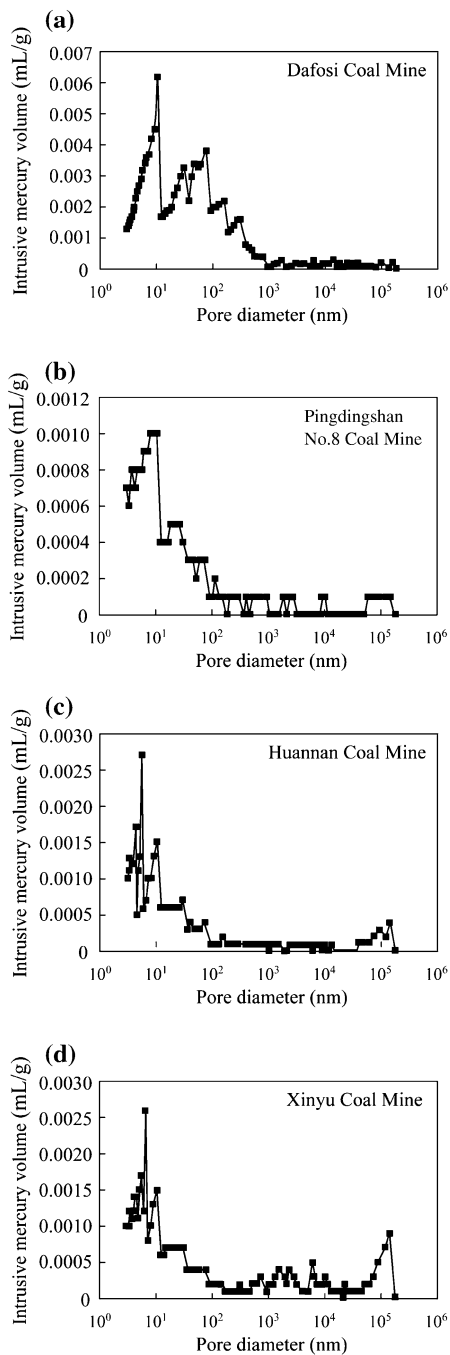
Fig. 2 Pore size distribution of coal samples

$42.317\ \mathrm{m^2/g}$, respectively. These properties are significantly higher than those of medium- and high-rank coal samples. Moreover, the permeability and porosity of low-rank coal are relatively high. Larger pore volume and specific surface area are conducive to gas storage and aggregation, whereas higher permeability will promote gas flow in the coal seam.

3 Effect of gas desorption in Jurassic low-rank coal beds

The proportion of mesopores and macropores in coal samples, as shown in Fig. 3, can be obtained from the gas adsorption experiments and mercury injection experiments.

Figure 3a illustrates that the proportion of the slit-shaped macropores in Jurassic low-rank coal reaches 31.66 % and the permeability of macropores reaches 10.34 mD, which promotes gas flow in high-pressure stages. However, the percentage of the slit-shaped macropores in medium- and high-rank coals is relatively small. Figure 3b illustrates that semi-open inkpot-shaped mesopores in Jurassic low-rank coal account for 46.26 % of the total, which is significantly higher than that of the medium- and high-rank coal samples. Gas desorption at low-pressure stages is restricted by the 'bottleneck effect' of the semi-open inkpot-shaped mesopores and further weakens gas extraction.

Micropores are rarely developed in low-rank coal; mesopores are dominated by semi-open inkpot shapes whereas macropores are usually slit-shaped. The special pore structure of Jurassic low-rank coal results in a 'multi-stage controlling effect' on gas desorption. Gas desorption at high-pressure stages is mainly dominated by the slit-shaped macropores; gas can be rapidly released with large flow rates and high concentrations. Because gas desorption at low-pressure stages is mainly dominated by semi-open inkpot-shaped mesopores, gas desorption is severely limited; the flow rate and concentration decay rapidly with abrupt mutations. Such uneven extraction would lead to a large amount of remanent gas, greatly restricting the simultaneous extraction of coal and gas. Therefore, it is
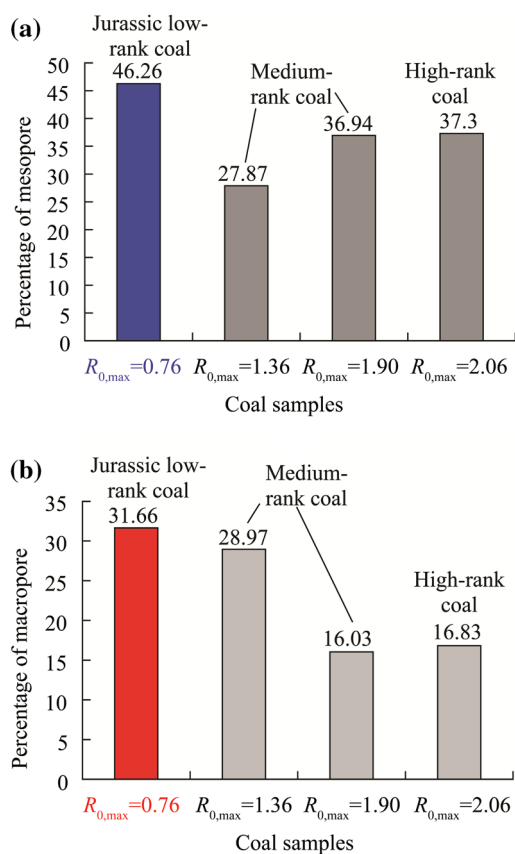
Fig. 3 Proportion of mesopores and macropores in coal samples

essential to establish an efficient gas extraction model to realize the stepped exploitation of gas.

4 Gas extraction model for low-rank high-gas coal beds

4.1 'Two-three-two' gas extraction model

On the basis of the special pore structure of Jurassic low-rank coal and the space–time replacement law for coal production, a 'two-three-two' gas extraction model was proposed (Fig. 4). In this model, gas extraction is divided into three periods: a planning period, a transitional period and a production period. In each period, surface extraction and underground extraction are performed simultaneously, and pressure-relief and conventional extraction are coupled to each other. Using this model, surface well gas extraction was first applied in the Dafosi Coal Mine in December 2009. Gas extraction maintained high efficiency in the early period of the engineering project, and the highest daily output of an individual well reached 16 582.3 m³. However, as time went on, the coal bed entered a low-pressure stage. Gas desorption becomes more and more

difficult and the gas extraction quantity rapidly decays. Thus, underground extraction is extremely urgent to debase the gas content of the coal seam.

The planning period corresponds to the 5–10 years prior to the underground exploitation of the coal mine. In this period, large quantities of surface wells would be arranged to pre-extract the coalbed methane. The arrangement of the surface wells (type, orientation and density) should coordinate with factors of geology, geography and resource. Well densification or multiple-branch horizontal wells should be applied in gas-rich area. At the meantime, the relative location of surface wells and underground roadways should also be taken into consideration to avoid any adverse effects on coal production. After the well drilling has been completed, hydraulic fracturing would be adopted to form a fractured zone in the coal seam. At high-pressure stages, large quantities of gas were desorbed and extracted through the fractured zone and the wells. When the decay of the gas-extraction quantity occurs, the gas extraction enters the transitional period.

The transitional period corresponds to the underground exploitation period, when roadways are gradually constructed while coal mining is not being carried out. As the pre-extraction area is full of the original coal mass that has not been induced by mining, fractures are gradually closed under in situ stress and, as a result, gas flow is hampered. At this point, long horizontally striking boreholes should be drilled from roadways along the coal seam to intersect the fractured zone, forming a local stripped pressure-relief zone. The surface wells together with long boreholes jointly extract gas. In addition, extraction by excavation, pre-extraction before mining and pre-extraction of adjacent panels should also be carried out to eliminate blank areas of gas extraction.

The formation of the mining face marks the beginning of the production period, when the decrease of gas-extraction in surface wells and long boreholes runs counter to the urgent demands of production. During the planning and transitional periods, the geostress is relatively high and fracture development is weak. Limited effects of gas extraction can be achieved. Therefore, the pressure-relief effects induced by mining should be taken advantage of in the production period. Additionally, crossing boreholes from elevated lanes should be undertaken to avoid gas overrunning at the mining face.

4.2 Staged division of gas extraction

To assess the efficiency of gas extraction over different periods, a mathematical model of the permissive coal-bed gas content for safe coal mining was established considering factors such as coal-bed gas geology, coal mining activity and mine ventilation (Qin et al. 2007):
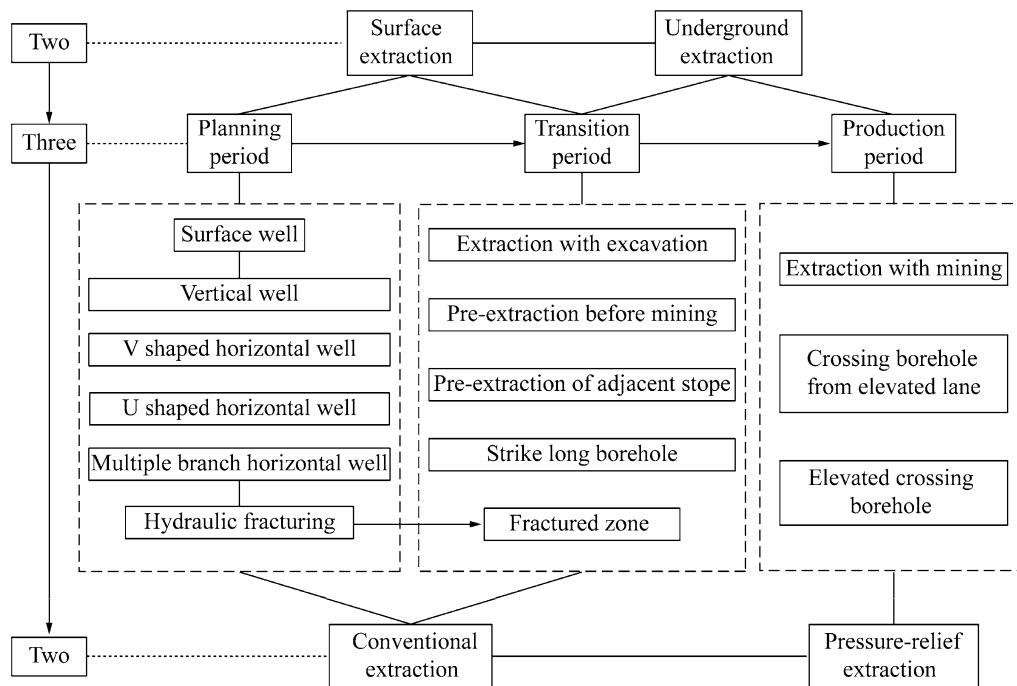
Fig. 4 The 'two-three-two' model of gas extraction in low-rank high-gas coal beds
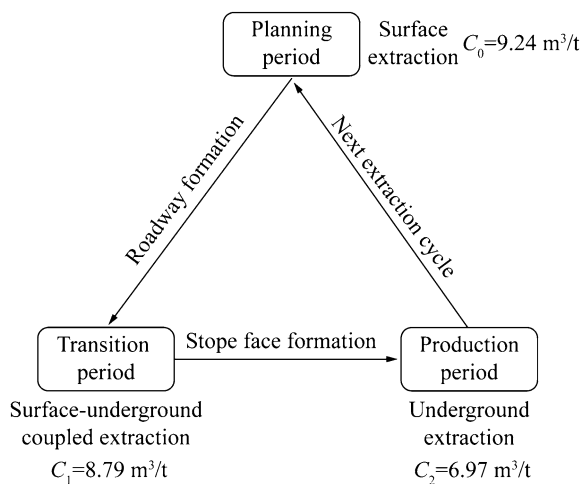

Fig. 5 Staged division of gas extraction in the Dafosi Coal Mine

$$C = C_{ic}(1 - R) + \beta\varepsilon\frac{M_c S_h v_h}{nP}, \qquad (1)$$

where C_{ic} is the original gas content of the coal bed (m³/t); R is the gas desorption ratio (%); β is the recovery ratio of coal resource (%); ε is a combined influence factor; M_c is the permitted volume fraction of gas in the ventilation roadway (%); S_h is the sectional area of the ventilation roadway (m²); v_h is the permitted air speed in the ventilation roadway (m/s); n is the ratio of the affected distance

in front of the excavation face to the excavation speed; and P is the coal production (t/s).

After substitution of the relevant parameters from the Dafosi Coal Mine into Eq. (1), a division criterion for gas extraction can be obtained (Fig. 5). According to the gas extraction rate of the Dafosi Coal Mine (73.2 %), the proportion of gas extraction periods can be calculated: 3.2 %–6.6 % for the planning period (with an average of 4.9 %), 17.3 %–22.3 % for the transitional period (with an average of 19.8 %), and 47.8 %–49.3 % for the production period (average of 48.5 %). The proportions of gas extraction in the Dafosi Coal Mine are shown in Fig. 6. Note that the production can be dynamically adjusted by the mining deployment and geological conditions. Therefore, we can form a flexible and efficient gas extraction system.

5 Applications

In this section, the gas extraction effect of the 'two-three-two' gas extraction model is investigated, taking panel 40110 from the Dafosi Coal Mine as an example. The exploitable reserves, original gas content and total gas content of panel 40110 are 3.55×10^6 tons, 9.2 m³/t and 32.66×10^6 m³, respectively. The roadway layout for panel 40110 is illustrated in Fig. 7.

The planning period: DFS-01 surface well covers panel 40110. Gas extraction from this well commenced on 4 July
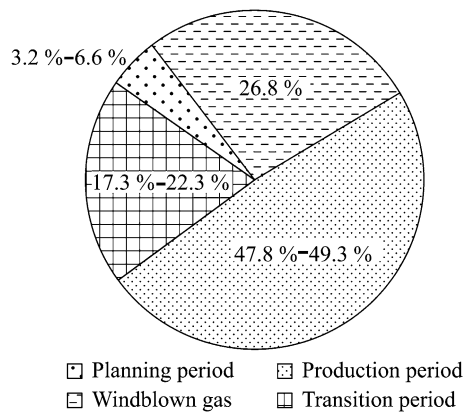
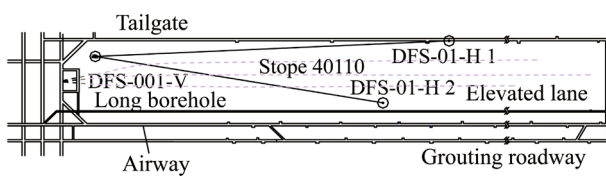Fig. 6 Proportions of gas extraction in the Dafosi Coal Mine

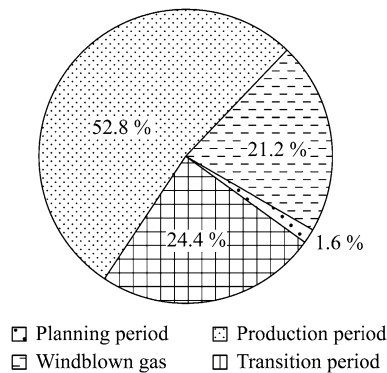Fig. 7 Roadway layout of the panel 40110 in the Dafosi Coal Mine

Fig. 8 Proportions of gas extracted from panel 40110 in the Dafosi Coal Mine

2009 and ended on 12 March 2011 (a total of 617 days) induced by the mining activities at panel 40108. The cumulative gas production during this period was 416×10^3 m^3.

The transitional period: gas extraction during the transitional period consists of the combined extraction from the DFS-01 surface well and the underground long boreholes, the extraction with excavation of the tailgate, airway and grouting roadway of panel and pre-extraction of panel 40110. The total gas production was up to 807×10^6 m^3.

The production period: gas extraction during the production period consists of mining panel 40110 and the area of the crossing boreholes from the elevated lane and the

grouting roadway. The total gas production was up to 17.23×10^6 m^3.

After applying the 'two-three-two' gas extraction model, the gas extraction rate for panel 40110 reached 78.8 %, which exceeds the original rate (73.2 %). The proportion of gas extraction from panel 40110 over the three periods is presented in Fig. 8. Compared with Fig. 6, the proportion of gas extracted in the planning period (1.6 %) is lower than the theoretical value (3.2 %–6.6 %), resulting in an increase in gas extraction rates for the transitional and production periods. The lack of surface extraction may put greater pressure on underground mining. Therefore, we suggest that the surface extraction in this area should be extended or densified.

We will investigate the extraction situation for the DFS-02-V surface well in the following section. Coal and gas storage capabilities in the area around this well are 12×10^6 tons and 110.49×10^6 m^3, respectively. Up to 30 August 2013, the cumulative gas production of this well was 841.63×10^6 m^3. The proportion of gas extracted during the planning period (10.4 %) is higher than the theoretical value (3.2 %–6.6 %). Thus the extraction in the planning period has already risen to the standard quality, and can be attributed to the transitional period. Owing to the large proportion extracted in the planning period, the transitional and production periods can be reduced, appropriately. The quantity of boreholes should be reduced and the extraction duration shortened to affect rapid production.

6 Conclusions

(1)   Micropores are relatively rare in low-rank coal; mesopores usually have semi-open inkpot shapes whereas macropores are usually slit-shaped. At high-pressure stages, gas desorption is mainly dominated by the slit-shaped macropores. Gas can be rapidly released with high flow rates and concentrations. In contrast, during low-pressure stages, gas desorption is mainly dominated by the semi-open inkpot-shaped mesopores. Gas desorption is severely limited. Both the flow rate and concentration decay rapidly with abrupt mutations.

(2)   A 'two-three-two' gas extraction model was developed based on the combination of experimental analysis and engineering practice in the Binchang mining area. In this model, gas extraction is divided into three periods: a planning period, a transitional period and a production period. In each period, surface and underground extraction are undertaken simultaneously. In addition, pressure-relief and conventional extraction are coupled to each other.

(3) Based on gas extraction rates at the Dafosi Coal Mine, the proportions of gas extraction periods were calculated. After applying the 'two-three-two' gas extraction model, the gas extraction rate for panel 40110 reached 78.8 %. Production can be dynamically adjusted by mining deployments and geological conditions so that a flexible and efficient gas extraction system can be formed.

References

Duan XQ, Qu JW, Wang ZN (2009a) Pore structure of macerals from a low rank bituminous. J China Univ Min Technol 38(2):224–228

Duan XQ, Qu JW, Wang ZN (2009b) Wettability of macerals from low rank bituminous. J China Coal Soc 34(2):243–246

Fu XK, Huo YZ, Hu AM, Fan ZQ (2006) Exploration and development of low rank seam coal bed methane in America. China Coal 5:75–76

Han DX (1980) Coalfield geology in China, Beijing

Jiang WP, Song XZ, Zhong LW (2011) Research on the pore properties of different coal body structure coals and the effects on gas outburst based on the low-temperature nitrogen adsorption method. J China Coal Soc 36(4):609–614

Kondo JY, Ishikawa DX, Abe YF (2006) Adsorption Science, Beijing

Li ZW, Lin BQ, Hao ZY, Gao YB (2013) Characteristics of pore size distribution of coal and its impacts on gas adsorption. J China Univ Min Technol 6:1047–1053

Li GF, Li B, Jiao HB, Liu X (2014) Three-region integrated CBM stereo-extraction in Jincheng mining area. China Coalbed Methane 11(1):3–7

Lin BQ (2010) Theory and techniques of coal mine gas control. Xuzhou, China University of Mining and Technology Press

Liu Y, Gao XK (2014) Reservoir forming characters of low-rank CBM in Binchang block, Ordos basin. Reserv Eval Dev 4(2):70–75

Liu HB, Hu SB, Yin RS, Cao J, Wang F (2011) Occurrence features of coalbed methane of Binchang mining area in Ordos basin. Coal Geol Explor 39(4):20–23

Qiao JW (2009) Research on the low rank coal of pore characteristics and desorption laws, Xi'an University of Science and Technology

Qin Y, Ye JP (1999) Characteristics and mechanism of gas controlling in the factor of rock physics in China coal reservoir. J China Univ Min Technol 28(1):14–19

Qin Y, Wu CF, Hu AM, Yang ZB, Fan ZQ, Ye JP (2007) Mathematical model of permissive coalbed-gas content for safe coal-mining. J China Coal Soc 32(10):1009–1013

Qin Y, Yuan L, Hu QT, Ye JP, Hu AM, Shen BH, Cheng YP, He XQ, Zhang SA, Li GF, Zhang Q (2012) Status and development orientation of coal bed methane exploration and development technology in China. Coal Sci Technol 10:1–6

Sun P, Wang B, Sun FJ, Zheng GQ, Li GZ, Wang HY, Liu HL, Deng Z (2009) Research on reservoir patterns of low-rank coal-bed methane in China. Acta Petrolei Sin 30(5):648–653

Tian C, Tang DZ, Zhou ZJ, Tao S, Chen XZ, Song CL (2012) Hydrogeological characteristics and their control on coalbed methane in Binchang mining area. Coal Geol Explor 40(1):43–46

Ye X, Chen CF, Jiang WL, Deng HC, Xu CH (2009) Geological characteristics and new development progress of low rank seam coalbed methane in China. Coal Sci Technol 8:111–115