A sequential approach to control gas for the extraction of multi-gassy coal seams from traditional gas well drainage to mining-induced stress relief

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HIGHLIGHTS

- The gas reservoirs characteristics are measured and analyzed.
- A sequential approach to control gas of multi-gassy coal seams is proposed.
- The design of gas drainage wells has been improved.
- The utilization ways of different concentrations of gas production are shown.

ABSTRACT

As coal resources become exhausted in shallow mines, mining operations will inevitably progress from shallow depth to deep and gassy seams due to increased demands for more coal products. However, during the extraction process of deeper and gasser coal seams, new challenges to current gas control methods have emerged, these include the conflict between the coal mine safety and the economic benefits, the difficulties in reservoirs improvement, as well as the imbalance between pre-gas drainage, roadway development and coal mining. To solve these problems, a sequential approach is introduced in this paper. Three fundamental principles are proposed: the mining-induced stress relief effect of the first-mined coalbed should be sufficient to improve the permeability of the others; the coal resource of the first-mined seams must be abundant to guarantee the economic benefits; the arrangement of the vertical wells must fit the underground mining panel. Tunlan coal mine is taken as a typical example to demonstrate the effectiveness of this approach. The approach of integrating surface coalbed methane (CBM) exploitation with underground gas control technologies brings three major benefits: the improvement of underground coal mining safety, the implementation of CBM extraction, and the reduction of greenhouse gas emissions. This practice could be used as a valuable example for other coal mines having similar geological conditions.

1. Introduction

The strong dependence of Chinese economic development on energy has led to the increasing use of coal products [1,2], which accounts for 70% of the nation’s total energy supply [3]. Industrial coal consumption from 2008 to 2035 is expected to grow by 67% [4]. As a result, the mining depth of coalbeds has increased annually by 10–50 m from shallow to deep deposits. The recoverable reserves of coal resources, which is deeper than 1000 m, account for 2.95 trillion tons, or nearly 53% of the total reserves [5]. Based on the demands for coal and the abundance of deep resources, the shift of mining depths from shallow to deep will be inevitable.

With the increase of the mining depth, more and more low gassy mines will be replaced by high gassy outburst-prone mines. The protective seam mining and underground gas pre-drainage are the primary measures to reduce the gas content and to control the outburst [6]. Protective seam measure, through mining the low gassy coalbed (called protective seam) for releasing the gas in adjacent high gassy coalbeds (called protected seam) to ensure the
safety in mining process, has been widely used in the coal fields of Huainan, HuaiBei, Yangquan, Shenyang and other regions [7]. The application of these measures in different geological conditions – short-interburden protective seam [8], distant-interburden protective coal seams [9], and extra-thin protective seam [10] – have been studied by many scholars. The regional pre-drainage measure, i.e., degassing the in situ coalbed through underground boreholes [11], has been used in many coal fields without the use of the protective seam mining measure.

However, for gas control in a deep and gassy multi-coalbed location, a new challenge exists not only in the protective seam mining but also in the regional gas pre-drainage. For protective seam mining, it is difficult to find the appropriate coalbed to be first-mined as the protective seam, because almost all the coalbeds have the risk of an outburst, while the less risky coalbeds are either too thin or high ash content with no economic value to mine. For gas pre-drainage, it requires adequate roadways in strata and boreholes to ensure the effectiveness of drainage. The maintenance costs associated with roadways in deep strata are unavoidable. In a multiple-coalbed formations, a large volume of pressure-relief gas from adjacent coalbeds will migrate into active mining panels as a result of mining excavations. This situation causes the gas emissions of coal mines to increase dramatically to hundreds of cubic meters per minute. The output of coal production is consequently limited by the prevailing ventilation system, due to the excessive high gas emission.

Known as a hazard to mining safety and a powerful greenhouse gas, coalbed methane is also a form of clean and efficient energy [12]. The CBM industry are well-developed in America, Canada, Australia, Poland [13–17] and also in China [18,19]. Surface vertical wells have been introduced to the field of gas control in underground coal mines. The functions of vertical wells can be classified into three major categories: firstly, to conduct hydro-fracturing and improve coalbed gas reservoirs for CBM recovery from surface; secondly, to drain the pressure relief CBM resulting from mining activities [20]; thirdly, to perform gob gas drainage after the coalbed was mined [21,22]. But in most cases, the CBM projects which have been run as a standalone system are not related to the mining process of the coal mine.

Aiming at the problems mentioned above, a concept of gas control was proposed. In general, it can be divided into three stages in chronological order: stage one, the first-mined coalbed reservoir is selected and improved by surface vertical wells and hydro-fracturing to increase the reservoir permeability and eliminate the outburst risk. Stage two, the gas content will get lower by the enhanced underground gas drainage to ensure the efficient and safe mining of the first-mined coalbed. Stage three, during the mining process of the first-mined coalbed the permeability of other adjacent coalbeds will enhanced by the pressure-relief effect. Through the pressure-relief gas drainage by the surface vertical wells and underground boreholes, the outburst risk of all the coalbeds will be eliminated. By integrating the present coal mine gas control method with surface CBM extraction technologies, we improve the selection of the first-mined coalbed standard and maximize the usage of vertical well to achieve high-efficiency coal exploitation of coal and methane. The concept is implemented in practice in the Tunlan coal mine. This case study sets a good example for other coal mines with similar geological conditions.

2. Reservoir characteristics in Tunlan

The selection of Tunlan coal mine for a case study was significant because of following typical reasons: Firstly, it has characteristics of multi-coalbed formations and is generally representative of most of the coalfields in China; Secondly, as more coal mines are aging and have to explore coalbeds in greater depth, gas problems have become a bottleneck for resource exploitation. From 2004 to 2009, Tunlan mine exhibited a record of zero fatality in the metric of DRPMT (death rate per million tons), however, on 22nd February 2009, an extremely serious gas explosion occurred, causing 78 deaths and 114 injuries due to insufficient gas drainage [23]. As a key state-owned coal mine, Tunlan mine has received widespread attention and played an important role in gas control and mining safety.

2.1. Geology

As shown in Fig. 1, Tunlan coal mine is located in the middle part of the Xishan coalfield, which is one of the six major coalfields in Shanxi province at the northern rim of the Qingshui basin. The mine started operation in 2002 with a designed annual capacity of 4 million tons. The main coal bearing strata are the 100 m thick Taiyuan group in the upper series of the Permian and the 60 m thick Shanxi group in the lower series of the Carboniferous. The main minable coalbeds for economic production are the No. 2, No. 4, No. 8 and No. 9 seam, which have an average dip of 7° and are to be extracted by longwall mining method. The permeability of the main minable coalbeds is less than 0.01 md, which is unfavorable for gas drainage in virgin coalbeds. The sequence of the coalbeds is illustrated in Fig. 2.

2.2. Characteristics of gas reservoirs

2.2.1. Coal samples and preparation

The characteristics of the gas reservoirs depend on various deposition environments [24]. The variations of the overburden thickness over each coalbed may influence the sealing effect during methane migration in the hydrocarbon generation period. In the Yanshanian, the temperature field of the coal-bearing strata was changed by the magma intrusion, which resulted in different volumes of thermogenic gas [25,26]. To obtain better understanding of the reservoir characteristics, a series of tests were performed. One coal sample of each coalbed was taken from the tunneling or mining workspace (Table 1). The samples were sealed in the package from the site and prepared for the proximate analysis, petrographic analysis, pore size distribution tests and methane adsorption tests.

2.2.2. Method and tests

By using the Automatic Proximate Analyzer 5E-6600, the proximate analysis was performed according to the ISO 17246:2010 [27] test method with particle sizes of 0.074–0.2 mm. The maceral group composition was determined in accordance with the ISO 7403-3:2009 [28]. The pore size distribution was determined by following the ISO 15901-1:2005 [29], using the mercury intrusion method with the AUTOPORE IV 9500 porosimeter and the adsorption of CO2 method with a gas sorption instrument AUTOSORB-1. Following the GB/T19560-2008 [30] test method, the methane adsorption isotherm was tested at 303 K under standard atmospheric pressure. The samples were all air dried ash-free basis with particle sizes of 0.2–0.25 mm.

2.2.3. Results and discussions

The proximate and petrographic analysis results, as shown in Table 2, indicates that the four samples have similar content of moist, ash and volatile matter. All samples are low-moisture and with moderately ash content. The percentage of volatile and fixed carbon is approximately 20% and 60%, respectively.

Limited by the intrusion pressure, the mercury porosimeter can only be used to measure the distribution of pores larger than 3 nm. The total pore volume, total pore area and porosity of samples are given in Table 3.
The Dubinin–Radushkevich (D–R) [31] method was established for describing the adsorption acts of micropores in coal. Using the D–R method, provided by the AUTOSORB-1 program, we calculated the micropore volume and the surface area (Table 3). The micropores, especially those pores smaller than 2 nm [32], are the main contributors to the capacity of adsorption. For all the samples, the average micropore width ranged from 1.00 to 1.45 nm.

The descending order of Langmuir volume ($V_L$) of samples is TL-8, TL-9, TL-2 and TL-4, from 24.75 to 19.22 mL/g (Fig. 3). The $V_L$ represents the adsorption capacity of coal. The sequence in the micropore volume and the surface area of the samples indicate a similar trend. The same trend was observed by An, who tested 11 coal samples from the Huaibei coalfield [33]. From the results, the samples obtained from the Taiyuan group (TL-8, TL-9) exhibit larger $V_L$ than the samples from the Shanxi group (TL-2, TL-4), which indicates that the adsorption capacity in lower coalbeds is higher than the overlying seams.

### 2.3. Coalbed methane content and outburst risk analysis

In accordance with the China’s national standard [34], three indicators are given for the judgment of the outburst risk in a coalbed: (i) the actual dynamic phenomenon in mining; (ii) the quantity of gas emission per ton of casted coal; (iii) the indices of outburst risk such as gas pressure and gas content. If any of these conditions is satisfied, the outburst risk of a coalbed is confirmed.

The two main indicators of outburst risk are tested in the main minable coalbeds at Tunlan coal mine. Gas data exceeding the critical value [34] is shown in Fig. 4. According to the measured data, the variations of the gas pressure with the mining depth are predicted as shown in Fig. 5, by using the safety line method proposed by Wang [35]. The gradient of No. 2 coalbed (in upper group) is 0.43 MPa/hm, much lower than the No. 8 coalbed (0.81 MPa/hm).

![Fig. 1. Location of Tunlan coal mine.](image)

![Fig. 2. General stratigraphy of coal measures at Tunlan coal mine.](image)

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Coalbed</th>
<th>Site</th>
<th>Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TL-2</td>
<td>No. 2 coalbed</td>
<td>12,407 Workface</td>
<td>360</td>
</tr>
<tr>
<td>TL-4</td>
<td>No. 4 coalbed</td>
<td>12,401 Drainage roadway</td>
<td>340</td>
</tr>
<tr>
<td>TL-8</td>
<td>No. 8 coalbed</td>
<td>28,107 Transport roadway</td>
<td>290</td>
</tr>
<tr>
<td>TL-9</td>
<td>No. 9 coalbed</td>
<td>18,203 Drainage roadway</td>
<td>400</td>
</tr>
</tbody>
</table>

**Table 1**

Coal samples locations.
With the results of proximate analysis and the methane adsorption
isotherm, the gas contents of these coalbeds were calculated.
When the depth is over 400 m, both the gas pressure and the gas
content will exceed the critical value, i.e., the risk of outburst will
be very high in all coalbeds. Since the commencement of coal pro-
duction, four small outburst phenomena have been observed in the
South 5th mining panel (Table 4).

3. Reservoir improvement and integrated surface-underground
gas drainage method in high gassy coalbeds

On the basis of analyses, the different gradients of gas pressure
and contents and the outburst risk are confirmed. However, the
low permeability and high gas content in all minable coalbeds
are the hindrance to the traditional gas drainage measures. For
the CBM development, the different pressure systems have nega-
tive effect on exploration of the entire coalbed group [36,37].
Therefore, we designed an integrated way to control the gas and

Table 2
The results of the proximate analysis and petrographic analysis.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Moist (wt.%, ad)</th>
<th>Ash (wt.%, ad)</th>
<th>Volatile (wt.%, ad)</th>
<th>Fixed carbon (wt.%, ad)</th>
<th>Vitrinite (%)</th>
<th>Inertinite (%)</th>
<th>Clay (%)</th>
<th>Pyrite (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TL-2</td>
<td>0.83</td>
<td>18.23</td>
<td>19.85</td>
<td>64.87</td>
<td>92.05</td>
<td>1.50</td>
<td>5.80</td>
<td>0.65</td>
</tr>
<tr>
<td>TL-4</td>
<td>0.76</td>
<td>23.17</td>
<td>22.81</td>
<td>58.72</td>
<td>93.50</td>
<td>1.45</td>
<td>4.65</td>
<td>0.40</td>
</tr>
<tr>
<td>TL-8</td>
<td>1.09</td>
<td>20.27</td>
<td>21.83</td>
<td>61.47</td>
<td>87.40</td>
<td>1.65</td>
<td>3.35</td>
<td>7.60</td>
</tr>
<tr>
<td>TL-9</td>
<td>1.18</td>
<td>24.03</td>
<td>18.84</td>
<td>60.70</td>
<td>88.65</td>
<td>2.30</td>
<td>7.60</td>
<td>1.45</td>
</tr>
</tbody>
</table>

Table 3
Pore characteristics of samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Total intrusion volume (mL/g)</th>
<th>Total pore area (m²/g)</th>
<th>Porosity (%)</th>
<th>Micropore volume (mL/g)</th>
<th>Micropore surface area (m²/g)</th>
<th>Average micropore width (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TL-2</td>
<td>0.0334</td>
<td>16.997</td>
<td>4.10</td>
<td>0.0014</td>
<td>4.06</td>
<td>1.09</td>
</tr>
<tr>
<td>TL-4</td>
<td>0.0246</td>
<td>12.637</td>
<td>3.22</td>
<td>0.0007</td>
<td>1.93</td>
<td>1.00</td>
</tr>
<tr>
<td>TL-8</td>
<td>0.0392</td>
<td>17.729</td>
<td>4.96</td>
<td>0.0019</td>
<td>5.53</td>
<td>1.45</td>
</tr>
<tr>
<td>TL-9</td>
<td>0.0266</td>
<td>14.071</td>
<td>3.51</td>
<td>0.0019</td>
<td>5.43</td>
<td>1.15</td>
</tr>
</tbody>
</table>

Fig. 3. Methane adsorption isotherm of coal samples at STP.

Fig. 4. Gas pressure and gas content measured in the main minable coalbeds.
exploit the coalbed methane resource. The technological steps are shown in Fig. 6.

3.1. Selection of the first-mined coalbed

3.1.1. Model development

The selection of a reasonable first-mined coalbed is the first step and is thus the foundation of the entire approach. There are three fundamental principles of this approach. First, the mining-induced stress relief effect caused by the mining process of the first-mined coalbed must be sufficient to improve the permeability of the upper and lower adjacent reservoirs. That will activate the gas drainage in them. Second, the coal resource of the first-mined coalbed must be abundant to guarantee the economic benefits of the mining. Third, the arrangement of the vertical wells must take the layout of underground longwall panels into consideration.

In order to investigate the stress relief effect of each coalbed, FLAC\textsuperscript{3D} [38, 39] was used for calculating the stress and displacement distribution in different cases.

Based on the geological condition at Tunlan coal mine, the model was developed to include all the major coalbeds in its coal measures formations. The model covers an area of 500 m × 500 m and 202 m in height. To simulate the load of the 450 m overburden, a compressive stress of 10 MPa was imposed on the top of the model. Fig. 7 shows the 3D model geometry and boundary conditions. The Mohr–Coulomb failure criterion was selected for the simulation. The initial properties of the rock mass are listed in Table 5 according to the typical values of the Tunlan coal mine.

3.1.2. Case studies

There are five minable coalbeds in the Tunlan mine: No. 2, No. 4, No. 7, No. 8 and No. 9. However, the vertical distance of the No. 2 and No. 4 coalbeds is too close, with an interburden of even less than 10 m in some areas. The same situation also occurs between the No. 8 and No. 9 coalbeds. The height of the caved zone is generally 3–6 times the thickness of the mined coalbed [40]. If the No. 4 or No. 9 coalbeds were selected as the first-mined coalbed, the No. 2 and No. 8 coalbeds would be in the caved zone. Thus, in this

![Table 4](image)

**Table 4** Details of the observed dynamic activities.

<table>
<thead>
<tr>
<th>Time</th>
<th>Location</th>
<th>Sea level (m)</th>
<th>Overburden depth (m)</th>
<th>Quantity of coal (t)</th>
<th>Quantity of gas emission (m$^3$)</th>
<th>Quantity of gas emission per ton (m$^3$/t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>February 4, 2008</td>
<td>12,503 Return airway@840 m</td>
<td>+720</td>
<td>350</td>
<td>0.69</td>
<td>205</td>
<td>230</td>
</tr>
<tr>
<td>February 8, 2008</td>
<td>12,503 Return airway@848 m</td>
<td>+720</td>
<td>350</td>
<td>0.41</td>
<td>82</td>
<td>200</td>
</tr>
<tr>
<td>February 21, 2008</td>
<td>12,503 Drawing roadway @ 842 m</td>
<td>+720</td>
<td>350</td>
<td>3.41</td>
<td>117</td>
<td>34</td>
</tr>
<tr>
<td>June 19, 2008</td>
<td>12,503 Return airway@1090 m</td>
<td>+610</td>
<td>360</td>
<td>0.57</td>
<td>22</td>
<td>39</td>
</tr>
</tbody>
</table>

![Fig. 5](image)

**Fig. 5.** Variations of gas pressure and content in the No. 2 and No. 8 coalbeds.

![Fig. 6](image)

**Fig. 6.** Technological steps.
study, three Cases were selected for the numerical simulation: Case A: the No. 2 coalbed was chosen as the first-mined coalbed; Case B: the No. 7 coalbed was chosen as the first-mined coalbed, and finally the No. 8 coalbed was chosen as the first-mined coalbed for Case C (Table 6).

### 3.1.3. Results and discussions

The stress field will redistribute when the first-mined coalbed is excavated and the change of the vertical stress would indicate the extent of de-stress effect. Fig. 8 showed the redistributions of the vertical stress from the numerical simulations for the above three cases.

In the vertical projection of the first-mined coalbed’s excavated area, its adjacent coalbeds are de-stressed to varying magnitude. The coalbed further away from the first-mined coalbed tends to exhibit less de-stress effect. The vertical stress increases slightly under the effect of the abutment stress, which extends approximately 5–40 m beyond the vertical projection both in x- and y-direction. For example, in Case A, the peak vertical stress in the No. 4 coalbed, which is only 9 m away from the first-mined coalbed, increases to 18.1 MPa, almost 1.43 times higher than its original value. In comparison, in the No. 8 and No. 9 coalbeds, the vertical stresses only exhibit an increase of 2% and 0.7%, respectively.

To determine whether a significant outburst risk exists, the stress rule was applied. The critical stress relief value can be calculated by the following equation [41,42]:

$$|\sigma_{zc}| \leq (\cos^2 \alpha + \sin^2 \alpha)\gamma H$$

(1)

where $\sigma_{zc}$ is the stress perpendicular to the coalbed, $\alpha$ is the coal seam dip, $\delta$ is the lateral pressure coefficient, $\gamma$ is the bulk density and $H$ is the overburden depth of the initial outburst site. According to the conditions of the Tunlan coal mine, $\alpha$ is 0°, $\gamma$ is 25,000 kg/

**Table 5**

Rock mass initial properties.

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Density (kg/m³)</th>
<th>Bulk modulus (GPa)</th>
<th>Shear modulus (GPa)</th>
<th>Friction angle (°)</th>
<th>Cohesion (MPa)</th>
<th>Tensile strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>1450</td>
<td>1.5</td>
<td>1.2</td>
<td>18</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Mudstone</td>
<td>2250</td>
<td>2.8</td>
<td>2.1</td>
<td>25</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Sandstone</td>
<td>2500</td>
<td>2.1</td>
<td>1.5</td>
<td>22</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Fine-grained sandstone</td>
<td>2600</td>
<td>3.4</td>
<td>2.5</td>
<td>30</td>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td>Sandy mudstone</td>
<td>2800</td>
<td>3.9</td>
<td>3.5</td>
<td>33</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Limestone</td>
<td>2800</td>
<td>8.5</td>
<td>5.5</td>
<td>43</td>
<td>4.5</td>
<td>4.5</td>
</tr>
</tbody>
</table>

**Table 6**

Cases of the simulations.

<table>
<thead>
<tr>
<th>Case</th>
<th>First-mined coalbed</th>
<th>Range of excavation X:Y:Z (m)</th>
<th>Coalbed</th>
<th>Relative position</th>
<th>Distance to the first-mined coalbed (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case A</td>
<td>No. 2</td>
<td>180:100:3.3</td>
<td>No. 4</td>
<td>Lower pressure relief seam</td>
<td>9</td>
</tr>
<tr>
<td>Case B</td>
<td>No. 7</td>
<td>180:100:0.8</td>
<td>No. 4</td>
<td>Upper pressure relief seam</td>
<td>60</td>
</tr>
<tr>
<td>Case C</td>
<td>No. 8</td>
<td>180:100:3.4</td>
<td>No. 2</td>
<td>Upper pressure relief seam</td>
<td>77</td>
</tr>
</tbody>
</table>

![Fig. 7. Geometry and boundaries of the numerical simulation model.](image-url)
and $H$ is about 360 m (Table 4), which produces a vertical stress $\sigma_{zc}$ of 9 MPa.

As illustrated in Fig. 9, the performances on stress relief of coalbeds are various in different cases. In Case A the re-established vertical stresses in No. 8 and No. 9 coalbed is still maintained at a high level. That is attributes to the distance of the coalbeds. Generally, the vertical scope of effective pressure relief cause by the upper coalbed is no more than 60 m [7]. In Case B and Case C, the re-established vertical stresses in other minable coalbeds are lower than the critical value, which indicates that both of the No. 7 and No. 8 could be chosen as the first-mined coalbed.

If only the stress reduction performance was taken as the principles for selecting the first-mined coalbed, clearly, the No. 7 coalbed, as a traditional “protective seam”, would be the best choice. However, the economic benefits cannot be neglected in the engineering design. The thickness of the No. 7 coalbed is only 0.8 m, so another 0.4 m of surrounding rock is required to be excavated to match the minimum mechanized mining height in the Tunlan coal mine. The ash of raw coal excavated will account for over 40% and the calorific value will be less than 4200 kcal/kg. The unprofitable feature of the first-mined coalbed will reduce the output of the coal mine, thus impacting the development of the coal mine.

With all these factors taken into consideration, it is proposed to discard the traditional descending mining sequence method and establish a new selecting standard for the protective seam (also called the first-mined coalbed). In this study, the No. 8 coalbed was selected as the first-mined coalbed.

### 3.2 Integrated surface-underground gas drainage method

As shown in Fig. 6, there are three core technologies in this method: gas reservoir improvement and gas drainage in the first-mined coalbed by surface vertical wells, enhanced underground gas drainage, and reformation and integration of surface and underground gas drainage in adjacent coalbeds.

#### 3.2.1 Reservoir improvement and gas drainage in the first-mined coalbed by surface vertical wells

As illustrated in Fig. 5, the gas content of No. 8 coalbed is about 10–14 m$^3$/t in deep area, but the permeability is less than 0.01 md. To maintain high gas flow rate in the vertical drainage wells and to improve underground borehole gas drainage at a late stage, hydro-fracturing is needed to improve the permeability of the first-mined coalbed.

The arrangement of vertical wells, one of the most important factors in CBM exploitation, directly determines the results of fracturing and gas drainage performance. In traditional CBM program, it is often determined by the geological condition, the surface landscape and logistic condition [36]. In this study, in addition to all these conditions, the vertical wells must be arranged with due consideration of the layout of underground longwall panels as a reference.

Detected by the microseismograph, the fracture could extend to over 150 m. The effective radius of vertical well extraction reached 150–200 m, but the width of the longwall panel was 200–300 m. To achieve more effective drainage, the vertical wells can be designed to interconnect with the adjacent longwalls (Fig. 10).

At this stage, the emphasis is on the improvement and transformation of the gas reservoir as well as the pre-drainage of the first-mined coalbed. The goal is to make the gas content of the first-mined coalbed down to 8 m$^3$/t and eliminate the outburst risk, thereby provide a favorable condition for underground gas drainage at later stages.
3.2.2. Enhanced underground gas drainage in first-mined coalbed

After the stage one, the outburst risk of first-mined coalbed could be diminished. However, due to the great drainage radius and the uneven distribution of the coalbed, outburst risk still exists in some areas. In order to keep lowing the gas content and avoid any possible blind areas, where the gas is not extracted sufficiently, enhanced underground gas drainage is necessary to achieve efficient driving and mining.

With the development of directional drilling equipment and technologies, the underground directional longhole needs to be employed to meet the demands of intensified gas drainage [43–45]. To pre-drain seam gas ahead of roadway drivage, the longhole should cover the area of at least 15 m beyond the ribs of the roadway and 60 m ahead of the drivage direction. To ensure efficiency and reduce drainage lead time, the longhole spacing should be kept within the range of 3–5 m. As the roadway is being developed, the

**FLOW CHART**

- Reservoir reformation and gas pre-drainage in the first mined coalbed by vertical well
- Enhanced underground gas drainage in the first-mined coalbed by underground longhole
  - A: Pre-drainage in advance of drivaging
  - B: Pre-drainage in advance of mining
- High-efficiency and safe mining of the first-mined coalbed

Fig. 10. A schematic view of the arrangement of surface vertical wells.

Fig. 11. Schematic view of the underground intensified gas drainage.
longholes are drilled into the longwall panel. Due to the pre-drainage by the vertical wells, these holes are drilled at intervals of 8–10 m (Fig. 11).

The extraction by underground longholes could be more efficient to the vertical wells, because of the lower negative pressure of drainage and the larger contact area in the coalbeds. After a period of enhanced underground gas drainage, we expect that the gas content will be lower than 5 m$^3$/t to ensure the high yield in workface.

3.2.3. Reformation and integration of surface and underground gas drainage in adjacent coalbeds

When the first-mined coalbed is being mined, the permeability of other coalbeds is enhanced by the stress relief effect. The desorbed gas from the roof and floor coalbeds will migrate into the first-mined coalbed’s workface and will be captured by the vertical wells and the longholes (Fig. 12).

According to its source, the desorbed gas can be divided into three parts: a. from the upper No. 2 and No. 4 coalbeds; b. accumulated in the gob of the first-mined coalbed; c. from the floor coalbeds. The first two parts are mostly drained by the vertical wells, and the last part is controlled by the longholes drilled in the No. 9 coalbed. The surface-underground combined pressure relief gas drainage controls the gas emission in the first-mined coalbed mining workface and degasses other coalbeds to remove the potential of outburst risk for ensuring mining safety.

4. Field application

Faced with the problem of extraction in deep high-gassy coalbeds, the traditional gas drainage measures are incorporated effectively in this concept. But it’s needs several years to realize the whole project. In order to evaluate the effect in short-term, industrial tests of core technologies were carried out.

4.1. Reservoir improvement and gas drainage by surface vertical wells

Since June 2011, surface vertical wells have been drilled for experiment in the deep mining panel at Tunlan coal mine. By the end of 2012, a total of 112 wells were implemented to reformation the deep coalbed reservoirs. According to the locations of the surface wells, 18 gas drainage plants were built. The volume of drainage gas flows were monitored continuously by real time monitors. The accumulative
To maintain the efficiency, the drainage suction pressure was adjusted from 30 kPa up to 50 kPa. With the adjustment, the flow rate increased to 7 m³/min. During the entire drainage period, the average pure gas flow rate was about 3.39 m³/min, and the gas concentration was basically above 30%.

The gas content of 18,207 workface ranged from 8 to 11 m³/t with a median of 10 m³/t and the resource reserve was estimated at 0.96 million tons. After extraction of 29 months, 4.3 million cubic meters of gas had been drained. That means the gas content reduced approximately to 5.5 m³/t. During the mining process, the maximum of gas concentration in airflow reached only 0.47% with an average of 0.34%. The highly gas extraction rate, 54% on average, effectively guaranteed the mining yield and the security of the workface.

4.3. Underground gas drainage in the adjacent coalbeds

The experiment of pressure relief gas drainage was conducted during the mining of the 18,207 longwall panel. A test roadway in the No. 9 coalbed was developed before the start of longwall extraction under the 18,207 mining area. A total of 823 longholes with a diameter of 113 mm were drilled into both sides of the roadway at an interval of 3 m. The entire vertical projection of the 18,207 excavated area in the No. 9 coalbed was covered by 76,813 m of longholes.

The pressure relief boreholes started to drain gas when the 18,207 longwall was being mined. The mining activities in the No. 8 coalbed improved the permeability of the No. 9 coalbed and consequently increased the gas flow rate to 5.79 m³/min on average (Fig. 14), which is almost twice the rate of enhanced gas drainage in the No. 8 coalbed. From the experiment, the pressure relief gas drainage could decrease the gas content of the No. 9 coalbed and eliminate the outburst risk; in this manner, the problem of massive gas emission in the active longwall face is solved.

4.4. Technology integration

The core technologies involved in this study were independently tested in the field and proved to be effective. Currently, the mining activities have not yet fully extended to the deep area, therefore the total integration of the technologies has not been completely implemented. Recently, reservoir reconstruction and gas drainage by surface vertical wells have been conducted in the deep mining panels at Tunlan Mine. The complete integration of technologies is scheduled to be completed in the next 8–10 years.

4.5. The utilization of gas production

The integrated gas drainage method has been applied successfully in Tunlan coalmine. The gas extraction volume has reached 60 million cubic meters per year. The 3.7 million tons of coal's outburst risk is eliminated, safety reserves outstrip the designed production. The gas extraction rate of the mine has risen to 56.6%. The number of CH₄ overrunning accidents fell to 1 last year from 59 in 2010. The safety situation has been improved dramatically and guarantees the mine to obtain better economic efficiency. As a clean, efficient energy, gas has been used widely in Tunlan coalmine. It has two drainage systems for different concentration of the gas. The gas drained by the vertical wells, has been collected in the high concentration system and sent to the urban gas pipeline in Taiyuan city to meets the requirements for residents' daily life. The gas drained by the underground longholes has been gathered in low concentration system for the gas boiler, the peat drier and the power generation. The 10-tonnes-class gas boiler project takes about 13 million cubic meters gas per year. Two of the power generators with capacity of 4 × 3000 kW h consume almost 30 million
cubic meters gas every year. The average rate of gas consumption reaches 95%, and the utilization ratio reaches 90%. The schematic of the utilization is shown in Fig. 15.

On present trends, the output of the coal mine could reach 5 million tons per year by 2020. The usable volume of gas could reach 0.35 billion cubic meters per year which would reduce greenhouse emissions equivalent to 6 million tons of carbon dioxide.

5. Conclusions

With the increase of the mining depth, new challenges have gradually emerged. Taking the Tunlan coal mine as a typical case study, a concept of gas control in the deep gassy coalbeds was proposed in this paper. The main conclusions can be summarized as:

(1) The coalbeds exhibit differences in their reservoir characteristics. The micropore volume and the surface area of the coalbeds in lower group are higher than those in upper group. The methane adsorption capacities and the gas contents show the same tendency. Based on the actual dynamic phenomena and the indices, the outburst risk is confirmed in all of the reservoirs. Traditional gas control methods are less effective in these deep and high gassy coalbeds.

(2) A concept of gas control was proposed and implemented in practice at Tunlan coal mine as a typical case study. Based on numerical simulations and mining economic analysis, the high gassy No. 8 coalbed was selected as the first-mined coalbed and hydro-fractured to increase the reservoir permeability. Surface vertical wells and underground longholes were used to effectively reduce the gas content of the first-mined coalbed, thereby eliminating the outburst risk of the first-mined coalbed and ensuring the safety of mining activities. During the mining process of the first-mined coalbed, the permeability of the other coalbeds (No. 2, No. 4 and No. 9) was enhanced by the pressure-relief effect. The outburst risk of the upper No. 2 and No. 4 coalbeds was controlled by the gas drainage of the vertical wells. In the No. 9 coalbed, the outburst risk was eliminated by underground longholes drainage. Finally, the efficient co-exploitation of coal-methane was achieved.

(3) The core technologies of this approach were independently tested in the field and proven to be effective. The average pure methane flow rate per well could reach 619 m$^3$/d, and the methane concentration could remain at a level over 80%. It is expected the gas content of the deep area will fall to 8 m$^3$/t and the outburst risk will be eliminated in 8 years. The enhanced gas drainage and pressure relief gas drainage by longholes were found to be effective in the 18,207 long-wall workface. Currently the complete integration of the gas drainage technologies is being implemented at Tunlan coal mine and will be completed in 8–10 years. The promising results provide a valuable demonstration and reference for other coalbed reservoirs with similar geological conditions.

(4) The integrated gas drainage method has been applied successfully in Tunlan coalmine. The gas extraction volume increased greatly, meanwhile, the mining safety situation is improved and the greenhouse gas emission is reduced. This case study could be used as a valuable example for other coal mines having similar geological conditions.

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