Optimal selection of coal seam pressure-relief gas extraction technologies: a typical case of the Panyi Coal Mine, Huainan coalfield, China

Zheng Shang, Haifeng Wang, Yuanping Cheng, Bing Li, Jun Dong & Qingquan Liu


To link to this article: https://doi.org/10.1080/15567036.2019.1639853

Published online: 10 Jul 2019.

Submit your article to this journal

Article views: 49

View related articles

View Crossmark data
Optimal selection of coal seam pressure-relief gas extraction technologies: a typical case of the Panyi Coal Mine, Huainan coalfield, China

Zheng Shang\textsuperscript{a,b,c}, Haifeng Wang\textsuperscript{a,b,c}, Yuanping Cheng\textsuperscript{a,b,c}, Bing Li\textsuperscript{c}, Jun Dong\textsuperscript{a,b,c}, and Qingquan Liu\textsuperscript{a,b,c}

\textsuperscript{a}State Key Laboratory of Coal Resources and Mine Safety, School of Safety Engineering, China University of Mining and Technology, Xuzhou, China; \textsuperscript{b}National Engineering Research Center for Coal Gas Control, China University of Mining and Technology, Xuzhou, Jiangsu, China; \textsuperscript{c}School of Safety Engineering, China University of Mining and Technology, Xuzhou, Jiangsu, China

ABSTRACT
Pressure-relief gas extraction from a protected seam can be realized by surface well drilling and the use of net-like penetrating boreholes (NPB). The selection of the extraction mode is affected by the geological conditions, characteristics of the coal seam occurrence and inherent characteristics of the extraction mode. Based on a numerical simulation and field test, the Panyi Coal Mine in the Chinese Huainan coalfield is used as an example to study the effective extraction range, efficiency, cost, total amount extracted and applicable conditions of two methods. The results show that the average gas extraction concentration (93.8\%) and average extraction purity (28 m\textsuperscript{3}/min) of surface wells are higher than those (41.8\% and 17 m\textsuperscript{3}/min) of NPB by approximately 124.4\% and 64.7\%, respectively. The superiority of the extraction efficiency from the use of surface wells is obvious from intact wells. In addition, the unit methane control costs, methane drainage costs per cubic meter and construction period of surface drillings are less than those of the NPB. However, Surface drilling is easily restricted by poor wellbore stability and high surface environment requirements. This case study can provide valuable examples for other coal mines with similar geological conditions for the selection of pressure-relief gas treatment methods.

ARTICLE HISTORY
Received 29 March 2019
Revised 31 May 2019
Accepted 18 June 2019

KEYWORDS
Pressure-relief gas extraction; surface well drilling; net-like penetrating boreholes; comparative analysis; gas control

Introduction
With the development of the economy, coal mine methane (CMM), as a form of non-renewable clean energy, plays an important role in the environmental protection and economic development of China (Yuan 2016). The coal seam gas in China is deeply buried at 2000 meters, with shallow reserves of $3.681 \times 10^{13}$ m\textsuperscript{3}, and recoverable reserves of $1.087 \times 10^{13}$ m\textsuperscript{3} (Zhou et al. 2016). According to China’s “Thirteen-Five” plan, coal energy will remain energy source of China’s future development during 2020–2050 (National Development and Reform Commission, Administration 2016). With the deepening of the mining depth, both the gas pressure and content of the coal seam increase (Cheng and Yu 2003). The problem of coal and gas outburst is becoming increasingly serious, and poses a serious threat to mine production (Mark 2018; Packham, Cinar, and Moreby 2011). Currently, methane extraction is widely used throughout the world to reduce the possibility of gas disasters occurrence (Yuan 2013a). Permeability is an important parameter for evaluating the feasibility of gas drainage (Chen et al. 2013). Because of the complex occurrence conditions and low
permeability characteristics of coal seam, gas extraction is increasingly difficult (Han, Xie, and Shao 2016). A large number of scholars at home and abroad have made great achievements in the long-term efforts of gas extraction.

The method of mining a protective coal seam and performing methane pre-drainage in a pressure-relief coal seam can effectively eliminate the danger from gas outburst (Cheng, Yu, and Yuan 2004; Karacan et al. 2011). Most of the coal seams in China influenced by geological tectonic movement are considered to have developed into complex and soft structures (Cheng and Yu 2007). As a result, the permeability of the coal seams which is not more than $0.1 \times 10^{-3} \mu m^2$ (the lowest in the Beipiao coal field is $0.7 \times 10^{-4} \mu m^2$; the highest in the Fushun coal field is only $1.8 \times 10^{-3} \mu m^2$), are significantly lower than those in the San Juan and Black Warrior basin of the USA (Hu, Jiang, and Su 2000). Consequently, protective seam mining is the most effective method for achieving the safe and economic exploitation of an outburst coal seam (Dong et al. 2015). The coal seam located above the protective coal seam is called the upper protective coal seam, and the lower protective coal seam is located below the protected layer (Liu et al. 2010). Vertical cracks and delamination cracks in the protected layer will significantly increase the permeability of the overlying coal strata (Figure 1) (Karacan et al. 2006). In recent years, the main method for performing pressure-relief gas extraction in China is surface well drilling and net-like penetrating boreholes (NPB) extraction and depends on the different coal seams, gas occurrence, and geological conditions long-term exploration (Jin et al. 2016; Kong et al. 2014; Liu et al. 2011; Yuan 2013c).

NPB technology is the most rudimentary and widely used method in China for extracting pressure-relief methane (Figure 2 (a)) (Cheng, Fu, and Yu 2009; Liu, Zhou, et al. 2017). NPB extraction depends on the maneuverable layout of the extraction roadway and flexible adjustments of borehole parameters, which can be adaptable to the geological conditions in a variety of forms (Zhou et al. 2015). However, there are many problems with NPB technology, such as the requirement for a large amount engineering of the gas extraction roadway and borehole, high cost, and long...
extraction period (Tu 2013). Regarding the mining extending dependence, the problems of a soft rock support, ground temperature and pressure have become increasingly prominent, leading to gas disasters (Bao, Wei, and Neupane 2016; Bustin and Clarkson 1998). In this case, the negative effect on gas control and safe production in a deep mine are aggravated by the gas extraction method with a shallow roadway, and deep mining in highly gassy mines faces security, technical and economic challenges (Zhang et al. 2017).

Surface well drillings (Figure 2 (b)) were used to extract pressure-relief methane in the 1950s (Sang et al. 2010). After extensive research, Chinese scholars have made great progress in extracting pressure-relief methane from protected coal seams via surface well drillings. This type of drilling has good methane control not only by virtue of the large flow rate and range and high concentration methane extraction, but also by being divorced from the constraint of the engineering conditions of the mining roadway (Li, Li, and Gang 2014; Liu, Cheng, et al. 2017; Yang et al. 2014). Nevertheless, methane production of a single well will not be satisfactory because the unique occurrence conditions of coalbed methane and reservoir conditions in China (Zhang, Zhang, and Guo 2017). Therefore, due to a series of economic problems, such as a long investment recovery period and poor economic benefit of these enterprises, it is difficult to promote the coalbed methane industry via the development of coal bed methane by only depending on market behavior (Wu et al. 2018).

With the rapid progress of the coal industry in China, to ensure a safe, efficient, economic and green production period, more efficient and economical methods for pressure-relief gas extraction are required (Yuan 2013b). Moreover, gas disasters in a coal mine, such as gas outburst and gas explosion during coal mine production, are important unfavorable factors of coal mine safety and high efficiency exploitation (Shen, Liu, and Zhang 2007; Xie et al. 2011; Zhao et al. 2016). In China, the low gas concentration is the main factor limiting the CMM utilization rate (only 34%) (Yuan 2011). Surface well drillings and partial NPB for pressure-relief gas play key roles in achieving high concentration ($C_{\text{CH}_4} > 30\%$) (Huang et al. 2012). Although the surface well drillings and NPB are considered to be effective for draining pressure-relief gas, the results of CMM extraction vary because of the large difference in the coal seam occurrence and geological structure, which seriously affect the production safety and economic benefits of the coal mine in practical application (Salmachi 2015; Zhou 2007). Therefore, the performance and cost of two types of CMM extraction methods should be evaluated for coal mines before methane extraction is performed. On this basis, efficient and economical methane drainage methods should be chosen according to the geological conditions, coal seam occurrence and production period.

Choosing the appropriate pressure-relief methane drainage method before mining is significant for ensure the premise of coal mine safety as well as highly efficiency and economic production. It is difficult to evaluate the methane extraction methods before mining because the drainage process of
methane is comparatively complex and little literature has comprehensively discussed the issue of calculating the performance of pressure-relief methane extraction methods or the cost of methane control. In this paper, the drainage efficiency, control cost and applicable conditions of surface well drillings and NPB drainage methods taking as contrast objects for pressure-relief methane extraction, are defined. The Panyi Coal Mine, a deep coal mine that has experienced the most serious methane disasters in the Chinese Huainan coalfield, is taken as an example to calculate the performance of the pressure-relief methane extraction methods and the cost of methane control for two working faces with similar geological conditions and occurrence characteristics.

**Geological background**

The Panyi Coal Mine is a large and modern deep mine with complex geological structures in the Huainan mining field. There are 14 faults, with a drop of more than 20 m, and a large number of minor faults in the mine field (Figure 3). The F4 and F5 faults are mainly divided into three characteristic units (namely, I, II, and III). The existence of faults hinders the flow of methane from deep to shallow and leads to large difference in the gas occurrence characteristics. As the depth of the coal seam in the middle (II) is the deepest, the overall distribution gas content is high in the middle and low in both sides.

To compare and analyze the characteristics of pressure-relief methane extraction by two types of methane extraction technologies, the 2151(3) and 2322(2) working faces, which have with the same conditions in regard to geological structure, coal seam occurrence, and methane parameters, are considered. The strike and dip lengths of the 2151(3) working face are 970 m and 178 m, respectively. The strike and dip lengths of the 2322(2) working face are 1060 m and 160 m respectively. Table 1 lists the parameters of the thickness, firmness coefficient, permeability, methane pressure, methane content and initial speed of the methane diffusion of 11–2 and 13–1 seams in the II characteristic unit. The 11–2 and 13–1 seams are found to have the following characteristics: soft, low permeability, high methane pressure, high methane content and fast diffusion. To reduce the gas content and increase the gas recovery rate, the Panyi Coal Mine adopted the protective coal seam (11–2) mining technology to relieve stress from the overlying coal rock relieved. The increase of permeability via the development of fractures and the gas outburst danger of the protected coal seam (13–1) will be eliminated.

![Figure 3. Map showing the location of the study area and the geological structure outline of the Panyi Coal Mine.](image_url)
The original mining-induced stress redistribution of the protective coal seam in adjacent layers can cause the coal seams superjacent the roof and lower floor to move and deform towards the gob (Xu and Qian 2005). Three zones, namely, the caved, fractured and continuous deformation zones, and a heaving floor phenomenon will be occur because of the effects of the pressure-relief area located above these zones (Qian, Shi, and Xu 2003). The overlying strata along the advancing direction of the working face will pass over the coal wall supporting, separating and re-compacting areas (Palchik 2003). The separation and fracture behavior of the coal and rock layers will engender a large number of bedding cracks and penetrating cracks (Guo et al. 2012). However, the internal balance stress and structure in the fracture pore was broken by the pressure-relief effect, thereby enlarging the fracture pore volume and fracture connectivity (Gao, Xu, and Zhou 2011; Xue et al. 2018b). As a result, the permeability of the protected layer also significantly increases (Wang, Elsworth, and Liu 2013; Xue et al. 2017). The permeability model established in the literatures (Chen et al. 2016; Gilman and Beckie 2000; Liu et al. 2015; Pan and Connell 2012; Zhang et al. 2018) is as follows:

\[
\begin{align*}
\phi &= \frac{V_f}{V} \\
\frac{k}{k_0} &= \left(\frac{\phi}{\phi_0}\right)^3 \\
\frac{k}{k_0} &= \left(1 + \frac{\varepsilon_v}{\phi_0}\right)^3
\end{align*}
\]

where \( V_f \) is the fracture volume, \( m^3 \); \( V \) is the bulk volume of the coal body, \( m^3 \); \( k \) is the unloading coal permeability, \( m^2 \); \( k_0 \) the initial permeability of unloaded coal seam, \( m^2 \); \( \phi \) is fracture porosity of unloaded coal seams, \( \% \); \( \phi_0 \) is the initial fracture porosity of unloaded coal seams, \( \% \); \( \varepsilon_v \) is the volumetric strain of the coal body.

The stress-strain and permeability-strain curves reflect the failure and permeability evolution process of protective coal in the mining of a protective coal seam. The evolution of volumetric strain of protected coal seam can be obtained by the FLAC3D numerical simulation. Through analysis of the volumetric strain in the process of the stress-strain and permeability-strain curves, we can get the evolution process of permeability.

### Numerical simulation

According to the geological conditions of the Panyi Coal Mine, the FLAC3D simulation software is used for modeling analysis. As shown in Figure 4, the X direction, Y direction and Z direction of the model are 400 m, 700 m, 238.6 m, respectively; the coal seam and rock dip angle is 12°. The relevant mechanical parameters determined according to the empirical values quoted in the geological exploration report of the Panyi Coal Mine are shown in Table 2. The length of the face of the protective coal seam is 300m, extending from 200m to 500m in the Y direction; the width

---

Table 1: Coal and methane comprehensive parameters of seams 11–2 and 13–1 in the three feature units.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Seam 11–2</th>
<th>Seam 13–1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth (m)</td>
<td>650 680 620</td>
<td>580 610 560</td>
</tr>
<tr>
<td>Thickness (m)</td>
<td>1.83 1.83 1.83</td>
<td>4.64 4.64 4.64</td>
</tr>
<tr>
<td>Firmness coefficient</td>
<td>0.17 ~ 0.42 0.17 ~ 0.42 0.17 ~ 0.42</td>
<td>0.17 ~ 0.42 0.17 ~ 0.42 0.17 ~ 0.42</td>
</tr>
<tr>
<td>Permeability (mD)</td>
<td>0.02 0.02 0.02</td>
<td>0.004 0.004 0.004</td>
</tr>
<tr>
<td>Methane pressure (MPa)</td>
<td>1.3 1.8 0.5</td>
<td>2.4 3.58 1.2</td>
</tr>
<tr>
<td>Methane content (m3/t)</td>
<td>6.23 7.5 6.7</td>
<td>6.0 11.7 6.9</td>
</tr>
<tr>
<td>Initial speed of methane diffusion (mmHg)</td>
<td>12 12 12</td>
<td>15 15 15</td>
</tr>
</tbody>
</table>
of the coal seam is 200m, and the mining height of the coal seam is 2m. A compressive stress of 16MPa is applied on the top of the model to simulate the load of the 670m overlay. The Mohr-Coulomb failure criterion is used to evaluate the failure of the coal and rocks caused by coal seam excavation, and the post-failure strength of the coal and rocks is described using the strain-softening constitutive model.

Results and analysis
After the protective coal seam mining, the coal and rock mass above the middle of the working face will change from a triaxial compression state to expansion deformation state, and cave in the direction of goaf under gravity, forming the so-called unloading deformation. The evolution process of the vertical stress and expansion deformation of the protected coal seam is shown in Figure 5. The stress of the protected coal seam is released approximately linearly behind the protective coal seam face and the maximum stress drop reaches 14.2MPa. In the center of the gob, the stress experiences an initial increase, followed by a decrease, before finally stabilizing at 6.13 MPa. The speed of stress unloading near the return lane is much higher than that of the transport lane and reaches the peak value at the center part of the working face. The effect of pressure unloading is obvious along the direction of the working face.

It is generally believed that when the expansion deformation rate of the protected coal seam is greater than the critical value of 3‰, the effective pressure relief will result in an increase of permeability (SAWS, 2008, 2009). When the advancing distance of the working face is 300m, the overlying coal rock layer has an obvious displacement due to the increase of the vertical stress.
caused by the pressure-relief behavior. The plastic damage range of the overlying coal rock is amplified from bottom to top, and the height of both sides is higher than that of the center. In the strike direction, with the advance of the protective work face and increase of the mining length, the range of the overlying coal strata is constantly expanding. Because of the differences of the subsidence and sinking coefficient of the overlying coal strata, collapse, subsidence and separation gradually occur in the vertical direction of the working face. After the subsidence of the coal rock mass at different positions located in the protective coal seam roof peaks, the plastic damage distribution in the coal rock is low in the middle and high in both sides, with the horizontal displacement disappearing and subsidence gradually decreasing at both sides. The maximum displacement of the protected layer reaches the peak value of variation (741.34mm) and the area of the expansion deformation rate that exceeds 3‰ (the maximum value is 15.6‰) is 200m. In addition, according to the expansion of the deformation of the working face in the dip direction, the expansion deformation rate along the dip direction is found to first increase and then progressively decrease.

The change of the permeability in the advancing process of the working face can be determined by analyzing the change of the volume strain according to the vertical stress and expansion deformation of the protected coal seam. The whole permeability strain curve is similar to the stress-strain curve (Yang et al. 2011). When the working face advances is by 300 m, the fractures in the protected coal seam undergo compaction and expansion after mining and the permeability greatly increases. During the whole process of permeability change in 13–1 coal seam, the permeability value gradually increases in the initial stage. Then the stress around coal body reaches the critical value, and the coal mass destruction occurs rapidly, leading to a sharp increase in the permeability of protected coal seam, which could reach up to 2,700 times of the initial permeability.

Pressure-relief gas extraction

The performance of surface well drilling and NPB are evaluated through a numerical simulation. Hydro-mechanical effect has influence on gas seepage process (Xue et al. 2018c), considering this one will increase the uncertainty of coal seam property parameters (e.g., phase permeability, diffusion coefficient, capillary pressure, wettability) (Liu, Cheng, Zhou et al., 2014), in order to highlight the difference between the two gas extraction methods, the hydro-mechanical effect is neglected. The governing equations are expressed and solved by using COMSOL Multiphysics finite element analysis software.
**Control equation of pressure-relief methane migration**

The control equation for the gas flow in pressure-relief coal seam is as follows (Xia et al. 2014; Xue et al. 2018):

\[ \frac{\partial (c(1 - \phi))}{\partial t} + \frac{\partial (\rho \phi)}{\partial t} = -\nabla m - \nabla (\rho v) \]  

(2)

where \( c \) is the quantity of adsorbed gas per volume of coal matrix, kg/m\(^3\); \( \rho \) is the gas density, kg/m\(^3\); \( \phi \) is fracture porosity of unloaded coal seam, \%; \( m \) is the mass diffusion flux of the adsorbed gas, kg/(m\(^3\)·s); \( v \) is the gas velocity in the fracture, m/s.

For the coal matrix system, the diffusion is considered to be driven by the concentration gradient. The value of \( c \) can be obtained by using the Langmuir equation (Liu, Cheng, Liu, et al., 2017).

\[ c = \frac{p V_L M_c}{p + p_L V_m \rho_c} \]  

(3)

where \( V_L \) expresses the maximum adsorption capacity of coal, m\(^3\)/kg; \( p_L \) expresses the Langmuir pressure constant, Pa; \( p \) is the gas pressure of coal, Pa; \( V_m \) is the molar volume of methane under standard conditions, m\(^3\)/kg; \( \rho_c \) is the coal density, kg/m\(^3\); \( M_c \) is the molar mass of methane, kg/mol.

The gas diffusion in the coal matrix can be calculated using Fick’s law.

\[ m = -D \nabla c \]  

(4)

where \( D \) is the gas diffusion coefficient, m\(^2\)/s.

For the coal cracking system, the relationship between the gas density and pressure is the same as the ideal gas law, and can be expressed as:

\[ \rho = \frac{M_c}{R T} p \]  

(5)

where \( M_c \) is the molar mass of methane, kg/mol; \( R \) is the universal gas constant, J/(mol·K); \( T \) the thermodynamic temperature of coal, K.

According to Darcy’s law, the gas outflow in fractures can be expressed as:

\[ v = -\frac{k}{\mu} \nabla p \]  

(6)

where \( v \) is the gas velocity in the fracture, m/s; \( k \) is the unloading coal permeability, m\(^2\); \( \mu \) is the methane viscosity, Pa·s.

According to the above derivation, the control equation of the gas flow field under pressure unloading can be obtained as follows (Xia et al. 2015):

\[ \frac{\rho_c V_L M_c p_L (1 - \phi)}{V_m (p + p_L)^2} \frac{\partial p}{\partial t} + \frac{\rho_c p V_L M_c}{V_m (p + p_L)} \frac{\partial (1 - \phi)}{\partial t} + \frac{M_c}{R T} \left[ \phi \frac{\partial p}{\partial t} + p \frac{\partial \phi}{\partial t} \right] - \nabla \left( D \nabla c + \frac{\rho_k}{\mu} \nabla p \right) = 0 \]  

(7)

The initial and boundary conditions are the same as those in the literature (Liu, Cheng, Yuan, et al., 2014) on the basis of the actual stress state of the coal and rock strata.

**Comparative analysis of the effect of pressure-relief gas extraction**

To compare the performance of surface well drilling and NPB for pressure-relief gas, only the drainage effect of the protected coal seam is considered. The two-dimensional geometric models simplified by the three-dimensional models are shown in Figure 6.

The length of the NPB model is 200 m, width is 100 m, and \( l \) is the distance between boreholes. Three Cases are selected for numerical simulation: Case 1: the distance between boreholes is 30m; Case 2: the distance between boreholes is 40m; Case 3: the distance between boreholes is 50m. The
borehole group (4 holes) is located in the center of the model and the initial coordinates are (55, 50), (40, 50), and (25, 50) for Cases 1, 2, and 3, respectively. To study the maximum extraction radius of surface well drilling and to ensure the correctness of the model calculation results, the length and width of the model are 450m and 250m respectively and the drill hole is arranged in the center position. The input parameters of the protected coal seam model are derived from the laboratory or field measurements as well as the simulation results presented in chapter 3.3 and other documents (Table 3).

The methane pressure in the numerical simulation is converted into the relative gas pressure, to allow the analysis to be integrated with field data and to contrast the effect of surface well drilling and NPB methane drainage. Under the same drainage area and time, analyses of single surface well drilling and the different intervals of NPB for pressure-relief methane extraction are conducted in combination with the increment coefficient of the protected coal seam permeability in the section 3.3 in this paper. The gas pressure changes calculated for extractions at 1 d, 10 d, 20 d, 30 d, 40 d and 50 d are shown in Figure 7. Monitoring lines L1, L2 and L3 are used to monitor the gas pressure of the NPB model, and L4 is used to monitor the gas pressure of the surface well drilling model. The lines starting from the initial coordinates of the boreholes extend to the model boundary (Figure 8). Table 4 shows the gas pressure value and total amount of gas drainage in the three models of NPB and surface well drilling.

According to the pressure curve analysis of different layouts of NPB and surface well drilling, the NPB model extraction area is found to be divided into two strong and weak regions in the 50d extraction period; if the gas pressure is lower than 0.74MPa in the strong extraction area, the weak area is extracted. The areas of strong influence are 130 m and 170 m when the distances are 30 m and 40 m. When the borehole interval is 50 m, the minimum gas pressure drops to 1.12MPa.

**Table 3.** Property parameters used in the numerical simulation model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermodynamic temperature, T</td>
<td>293 K</td>
<td>Field test</td>
</tr>
<tr>
<td>Density of coal, ( \rho_c )</td>
<td>1250 kg/m(^3)</td>
<td>Laboratory test</td>
</tr>
<tr>
<td>Langmuir volume constant, ( V_L )</td>
<td>0.0228 m(^3)/kg</td>
<td>Laboratory test</td>
</tr>
<tr>
<td>Langmuir pressure constant, ( P_L )</td>
<td>1.41 MPa</td>
<td>Laboratory test</td>
</tr>
<tr>
<td>Langmuir volumetric strain constant, ( \varepsilon_L )</td>
<td>0.012</td>
<td>Laboratory test</td>
</tr>
<tr>
<td>Initial pressure of original coal seam, ( p_0 )</td>
<td>4.4 MPa</td>
<td>Field test</td>
</tr>
<tr>
<td>Passon’s ratio of coal, ( \nu_p )</td>
<td>0.339</td>
<td>Laboratory test</td>
</tr>
<tr>
<td>Initial fracture porosity of fractures, ( \nu )</td>
<td>0.012</td>
<td>Laboratory test</td>
</tr>
<tr>
<td>Initial gas permeability, ( k_0 )</td>
<td>0.000268 mD</td>
<td>Field test</td>
</tr>
<tr>
<td>Diffusion coefficient, ( D )</td>
<td>( 3.3 \times 10^{-12} ) m(^2)/s</td>
<td>Laboratory test</td>
</tr>
<tr>
<td>Molar mass of methane, ( M_c )</td>
<td>0.016 kg/mol</td>
<td>An et al. (2013)</td>
</tr>
<tr>
<td>Increment coefficient of coal permeability, ( x )</td>
<td>2700</td>
<td>Field test</td>
</tr>
<tr>
<td>Value of axial deformation, ( b )</td>
<td>15.633%</td>
<td>Field test</td>
</tr>
<tr>
<td>Moisture content of coal, ( M_{ad} )</td>
<td>1.69</td>
<td>Laboratory test</td>
</tr>
<tr>
<td>Ash content of coal, ( A_{ad} )</td>
<td>31.62</td>
<td>Laboratory test</td>
</tr>
<tr>
<td>Volatile content of coal, ( V_{daf} )</td>
<td>27.01</td>
<td>Laboratory test</td>
</tr>
<tr>
<td>In situ stress, ( F )</td>
<td>12.18 MPa</td>
<td>Liu, Cheng, Yuan, et al. (2014)</td>
</tr>
</tbody>
</table>
and there is no strong influence area. The gas pressure is reduced to less than 0.74 MPa by surface well drilling after 50d of extraction and the radius is approximately 200m.

Figure 8 shows that the pressure obviously drops at the early stage of gas extraction. The gas pressure drops to approximately 1 MPa within 20 days of extraction, leading to a gas pressure gradient and a smaller rate of decrease. With the increase of the extraction time, the gas pressure is progressively reduced, which indicates that gas extraction will be saturated with the increase of the

<table>
<thead>
<tr>
<th>Extraction way</th>
<th>10 d (MPa)</th>
<th>20 d (MPa)</th>
<th>30 d (MPa)</th>
<th>50 d (MPa)</th>
<th>Total extraction amount (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 m</td>
<td>1.69</td>
<td>1.14</td>
<td>0.8</td>
<td>0.49</td>
<td>44138</td>
</tr>
<tr>
<td>40 m</td>
<td>1.78</td>
<td>1.47</td>
<td>1.10</td>
<td>0.69</td>
<td>41629</td>
</tr>
<tr>
<td>50 m</td>
<td>1.95</td>
<td>1.58</td>
<td>1.37</td>
<td>1.12</td>
<td>36530</td>
</tr>
<tr>
<td>Surface drilling well</td>
<td>2.11</td>
<td>1.47</td>
<td>1.06</td>
<td>0.67</td>
<td>47380</td>
</tr>
</tbody>
</table>
extraction time. The smaller the distance of NPB, the more significant the decrease of the velocity of gas pressure gradient. However, the smaller the distance between boreholes, the smaller the range of the strong area and higher the cost of gas extraction. Aiming at gas control in the 13–1 coal seam of the Panyi Coal Mine, among the three types of borehole arrangements, the effect of 30m spacing extraction is the best. Although the gas pressure can be reduced to approximately 0.49 MPa, the range of the strong influence area cannot cover the protected work face. The 50m spacing is too far, resulting in a blind zone between the gas extraction area to ensure safety production. Therefore, the spacing of NPB is recommended to be 40 m, this configuration is the best choice in terms of the extraction efficiency, effective range of gas descent and extraction cost. In addition, with the further extension of the coal seam to the deep part, the gas storage characteristics will be unfavorable for gas extraction and the distance of the NPB should be appropriately reduced.

Field application

Based on the COMSOL Multiphysics simulation results, when the drilling interval is 40 m, the maximum area of extraction will reach the maximum value. If NPB is applied to the 2151(3) working face with a tendency of 178 m, then there will be a weak extraction area of approximately 20 m that cannot meet the requirements of safe production in the process of coal mining. However, increasing the number of boreholes or reducing the spacing between drilled holes will lead to an increase in both the quantity of boreholes and costs. Therefore, surface well drillings are adopted in the 2151 (1) test work face, and NPB is used in the 2352 (2) test work face.

Gas control technology of the panyi Coal Mine

Pressure-relief gas drainage using surface well drillings at the Panyi Coal Mine is shown in Figure 9. The 11–2 coal seam is selected as the protective layer to improve the 13–1 protected coal seam pressure relief ability and increase the permeability. Considering the influence of the geological structure, the first surface well drilling is arranged at a distance of 260 m from the open-off cut of the 2151(3) working face. To ensure that the effective drainage area is not less than the dip length of the 2151(3) working face, the distance between the #1 and #2 drilling wells is 260 m. The distance

Figure 9. Schematic diagram showing the surface drilling gas extraction design during the process of protective seam mining.
between the #2 and #3 drilling wells is 314 m, which ensures that the mining scope of the 13–1 coal seam in the protected layer is within the protection range of the surface wells.

Pressure-relief gas drainage using NPB at the Panyi Coal Mine is shown in Figure 10. The borehole is arranged at the center of the working face, and the spacing between drilling holes is set to 40m. The floor rock roadway of the 13–1 coal seam is arranged in the continuous deformation zone, and should maintain an appropriate distance from the 13–1 coal seam. The floor rock roadway of the 13–1 coal seam avoids the mining destruction of the 11–2 coal seam, and the tunnel into the 13–1 coal seam and dip angle of the drilling hole are too small, both of which lead to difficulties in construction. According to the FLAC\(^3\)D simulation results in chapter 3.3, the roadway is arranged in the intact and hard strata 30 m from the 13–1 coal seam.

**Extraction law of surface well drilling and NPB**

To ensure the accuracy of the comparison, the comparison of the extraction efficiencies considers data obtained from the beginning of the production of gas from surface well drilling to the mining stopping line to be analysis data. The law of pressure-relief gas extraction is shown in Figures 11–12. When the distance of the working face mined-line form the #1 drilling well is 4 m, the gas flow rate begins to appear and then becomes very low in its wake; subsequently, the gas flow rate gradually transform from low to high (up to 35m\(^3\)/min). After extracting for 48 d, the gas concentration suddenly decreased to zero. The pure flow rate of the well extraction reaches the maximum at approximately 10 d and then decreases rapidly, and maintaining this downward trend until the drilling is stopped, to below 5 m\(^3\)/min. The gas flow rates of the #2 and #3 drilling wells reach peaks of 35 m\(^3\)/min and 27 m\(^3\)/min, respectively, when the protective coal seam is mined out for 25 d and 210 d, respectively. The gas concentrations of the #1 and #2 drilling wells are set at relatively high levels, with an average concentration of more than 90%. The #3 drilling well has a large fluctuation in the extraction concentration, with a maximum of 90.4%, minimum of 19.2% and average concentration of 65.25%.

For the #2 drilling well, the gas can only be pre-drainage gas through the unrelieved range before the working face advances to the influence area. The initial permeability of the protected coal seam is

---

**Figure 10.** Schematic diagram showing the underground drilling gas extraction design during the process of protective seam mining.
not conducive to extraction, and the drainage flow is always maintained at a low level. As the working face advances throughout the drilling process, the pressure in the protected coal seam is relieved by the mining-induced phenomena. The deformation of the protected coal seam leads to the regeneration of the separated cracks and increase the permeability of the coal seam. Therefore, the gas concentration and flow rate rapidly increases. The pressure-relief gas in the effective drainage area of drilling is gradually reduced, and the high efficient extraction stage is completed. Although the effective extraction times of the #1 and #3 drilling wells is different from that of the #2 drilling well, the change trend of the gas extraction flow rates and concentrations of the #1 and #3 drilling wells is the same as those of #2 drilling. Correspondingly, during the whole experiment, the maximum drainage flow rate of NPB is 25 m$^3$/min, with an average of 17 m$^3$/min, which is relatively stable relative to the surface drilling. For NPB, the maximum concentration is 82.8% and the lowest concentration is 2.95%, with an average of 45.66%.

**Extraction effect of surface well drilling and NPB**

Figure 13 shows the total amount of pressure-relief gas extraction through the models of surface well drillings and NPB after 270d of field experiments. The dip and strike direction of the pressure relief zone of the protected layer are 970 m and 160 m respectively. It can be calculated that the total desorbing gas of the protected coal seam is $9.717 \times 10^6$ m$^3$ based on the original and desorption gas...
content of the coal seam in this area of 12 m$^3$/t and 10.3 m$^3$/t, respectively. The total amount of pressure-relief gas extraction by surface well drillings is approximately 6.987 $\times$ 10$^6$ m$^3$, of which, the gas extraction of the #1, #2 and #3 drilling wells are 6.91 $\times$ 10$^5$ m$^3$, 3.212 $\times$ 10$^6$ m$^3$ and 3.084 $\times$ 10$^6$ m$^3$, respectively. The #2 and #3 wells continue to be extracted until the working face advances to the stop mined-line. The total amount of pressure-relief gas extraction by NPB is 7.832 $\times$ 10$^6$ m$^3$. The residual gas volumes of the protected coal seam during the surface well drillings and NPB extraction are 2.73 $\times$ 10$^6$ m$^3$ and 1.885 $\times$ 10$^6$ m$^3$ and the extraction rates are 71.9% and 82.6%, respectively.

**Comparative analysis of costs**

The cost of gas control is mainly due to the cost of the gas control engineering system. Table 5 lists the gas control project quantity, duration and control costs of the gas control technology of surface well drillings and the NPB in the 13–1 coal seam. The total gas control cost can be calculated according to the engineering quantity and unit price. As shown in Figure 14, the gas drainage technology of surface well drilling has obvious advantages in terms of time and cost.

**Table 5.** Methane control total cost of penetrating borehole and surface wells.

<table>
<thead>
<tr>
<th>Gas extraction method</th>
<th>Engineering name</th>
<th>Engineering quantity</th>
<th>Unit price</th>
<th>Duration (month)</th>
<th>Cost (Yuan)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPB</td>
<td>Floor rock roadway</td>
<td>1100 m</td>
<td>12,000 Yuan/m</td>
<td>37</td>
<td>14,750,000</td>
</tr>
<tr>
<td></td>
<td>Penetrating borehole</td>
<td>5938 m</td>
<td>260 Yuan/m</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Surface well drillings</td>
<td>Well drillings</td>
<td>3 well drillings</td>
<td>3,500,000 Yuan/well drilling</td>
<td>21</td>
<td>10,500,000</td>
</tr>
</tbody>
</table>

Figure 13. Total gas production of NPB and surface wells.

Figure 14. Gas drainage technology of surface well drilling has obvious advantages in terms of time and cost.
The coal seam reserves of the protected working face can be calculated according to the following equation:

\[ Q = \frac{L \cdot M \cdot h \cdot \rho}{C_1} \]  

where \( Q \) is the mining reserves, t; \( L \) is the minable length in the strike direction, m; \( M \) is the minable length in the inclination direction, m; \( h \) is the minable thickness, m; and \( \rho \) is the apparent density of coal, t/m³.

The coal seam reserves calculated for the 2151 (3) and 2322 (3) working faces are 1.0014 Mt and 1.028 Mt, respectively, and the gas contents of the 2151 (3) and 2322 (3) working faces are \( 1.1716 \times 10^7 \) m³ and \( 1.2028 \times 10^7 \) m³, respectively. Table 6 lists the unit methane control costs and methane drainage costs per cubic meter of the gas control technologies of surface well drillings and NPB in the experimental stage. According to Figure 15, the surface well drillings gas control technology has obvious advantages in economic gas control compared to NPB.

**Table 6.** Comparison of penetrating borehole and surface wells.

<table>
<thead>
<tr>
<th>Contrastive term</th>
<th>Surface well drillings</th>
<th>NPB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit methane control cost (Yuan/t)</td>
<td>10.49</td>
<td>14.35</td>
</tr>
<tr>
<td>Methane drainage cost per cubic meter (Yuan/m³)</td>
<td>16.1</td>
<td>19.8</td>
</tr>
</tbody>
</table>

**Discussion**

**Extraction performance of surface well drilling and NPB**

Surface well drillings can achieve pre-drainage, mining-drainage and mined-drainage. Intercepting the drainage of the gob is effective for preventing the pressure-relief gas from flowing to the protective working face and upper-corner. Before coal seam mining, the arrangement of surface well drillings can be independent of the borehole operation, and the extraction system is safe and convenient to administer. The concentration of the extraction gas is generally more than 60%, allowing the gas to be directly utilized (Li 2018). However, the key problem of surface well drilling is poor stability of the well structure;
the stability of the well is influenced by the geological conditions, reservoir conditions, well position and its own structure. Therefore, the effect of pressure-relief gas extraction is difficult to evaluate. After completion of surface well drilling, the effective extraction range of the well will be changed by the different gas occurrence characteristics and geological conditions. Because the position and well structure cannot be adjusted, one is compelled to turn the well off and stop extraction, resulting in a waste of both resulting in the waste of time and money.

The NPB model can be used to systematically investigate the parameters of the expanded deformation and permeability change of the protected coal seam and can account for the re-arrangement of the penetrating boreholes by means of the adjustable borehole parameters. The NPB model can obtain an adequate and reliable effect, independent of the thickness and inclination angle of the protected coal seam. The technology requires the length of the rock roadway to be same as that in the strike direction of the protected work face, which has a large amount of engineering facilities and demands periodic upkeep. In conclusion, the merits and demerits of the two types of gas extraction technologies considered are shown in Figure 16.

**Recommendation regarding the selection of the extraction methods**

In production practice, the surface well drillings will be blocked and become impermeable when a quick sand bed exists around the drilling. The large mining depth and high mining speed will cause frequent periodic weighting in the working face and damage to the well structure due to the large shear stress. The well platform will also sink with the surface ground and fall below the water level of the coal mining subsidence area, resulting in flooding and destruction of the well platform and drainage pipeline. Therefore, there is no complex geomorphology, such as high mountains, deep valleys and lakes in the coal seam surface, which is beneficial for the gas drainage of the surface well drilling process.

The NPB is not affected by the ground conditions, however, it will be limited by the geological conditions and distance between the protective and protected coal seam. Because the coal seams are not
sufficiently far apart and the protective coal seam mining height is large, the floor rock roadway will be seriously damaged. In addition, the position of the rock roadway should meet the requirements of the NPB construction, and cannot be arranged in the fracture zone nor be too close to the protected coal seam to ensure the effective extraction area of the penetrating boreholes. Although application of NPB is obviously meant to improve the effect of coal mine gas control, in the coal mining laneway, there is usually not enough time to drain the pressure-relief gas after entering the coal seam.

It is necessary to evaluate the extraction efficiency, extraction cost and performance of the gas extraction technologies of surface well drilling and NPB and investigate the coal mine geological conditions and coal seam occurrence characteristics to choose the safest, most efficient and most economical gas control method in an analytical manner for coal mines. The application conditions of the two types of gas extraction technologies considered are shown in Figure 17. When a coal mine with the multi-protected coal seams has the characteristics of stability, high gas content and gas pressure, inadequate alternating of mining industry flat surface ground and so on, the surface well drilling should be of highest priority. Correspondingly, when the permeability enhancement effect must investigated and the protected coal seam is characterized by a large dip angle and complex landform, it is necessary to adopt the NPB model.

Conclusions

(1) The deformation and permeability distribution of the protected coal seam after pressure unloading were obtained by numerical simulation using FLAC3D software. In the process of advancing the protective working face, the deformation rate and increment of permeability along the dip and strike directions underwent increases, decreases and stabilization. The maximum deformation rate can reach 17.8‰, with the permeability increasing by 2700 times. Although the permeability declines in the middle part of the goaf, it still increases by 2–3 orders of magnitude.

(2) The performance of the 40 m distance between boreholes in the NPB model is best according to the COMSOL Multiphysics simulation. When the borehole spacing is 50 m, the gas pressure after extraction cannot meet the requirements of safe production; the effective area of a 30 m extraction cannot cover the whole dip direction of 2322(2) working face.

(3) During the 270 d field test, #1 drilling works for only 48 d and the #2 and #3 wells work for 219 d and 139 d, respectively. The total amount of gas extracted from surface well drilling ($6.987 	imes 10^6$ m$^3$) is lower than that of NPB ($7.832 	imes 10^6$ m$^3$). The average gas extraction
concentration (93.8%) and average extraction purity (28 m³/min) of surface wells are higher than those of NPB (41.8% and 17 m³/min) by approximately 124.4% and 64.7%, respectively. A similar behavior was observed for the costs of unit methane control and methane drainage per cubic meter. It should be noted that the stability of the surface wells cannot do better than that of NPB.

(4) The application conditions of surface wells and NPB methods are summarized. When a coal mine with the multi-protected coal seams has the characteristics of stability, high gas content and gas pressure, inadequate alternating of mining industry flat surface ground and so on, the surface well drilling should be of highest priority. Correspondingly, when the permeability enhancement effect must be investigated and the protected coal seam is characterized by a large dip angle and complex landform, it is necessary to adopt the NPB model. This case study can provide valuable examples for other coal mines with similar geological conditions for the selection of pressure-relief gas treatment methods.

Acknowledgments

The authors are grateful for the support from the National Science Foundation of China (No. 51474212 and 51874297) and State Key Laboratory of Coal Resources and Safe Mining, CUMT (SKLCRSM16X03) and A Project Funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD).

Funding

This work was supported by the National Natural Science Foundation of China [51474212,51874297].
References


