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Research Article

Effects of Borehole Arrangement on Methane Migration and Implications for High Efficiency Extraction in Intact and Tectonic Combined Coal Seams

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Gas extraction by bedding boreholes is a key means to realize safe mining of coal mine and protect the environment. The traditional bedding boreholes are usually constructed in the center of the coal seam, which may not obtain a high methane extraction rate because of the existence of tectonic coal sublayer with low permeability. In this paper, the gas migration characteristics of combined coal seams composed of tectonic and intact coal sublayers are investigated, and the efficient gas extraction method is further explored. The results indicate that only 2.676 kg/m^3 of gas can be extracted under the traditional bedding borehole arrangement in 300 days. The tectonic coal sublayer with low permeability restricts the gas in the intact coal sublayers to flow to the extraction boreholes, which is the main reason for the low gas extraction rate. By arranging boreholes up and down alternately with a vertical spacing of 2.74 m, the maximum gas amount of 3.526 kg/m^3 can be extracted, showing an increased rate of 31.8%. The optimal vertical spacing between adjacent boreholes (VSAB) raises with the relatively increasing thickness or decreasing permeability of the tectonic coal sublayer. The optimal VSAB has a linear relationship with the thickness ratio of the tectonic coal sublayer to the combined coal seams. The optimal VSAB can be obtained referring to the numerical relationship, and then, the extraction boreholes can be dilled to achieve efficient gas extraction of combined coal seams. In engineering, the dislocation arrangement of borehole can greatly improve the gas extraction efficiency and coal mine safety.

1. Introduction

In China, coal will still be the main energy in the coming decades and also play an important role in clean energy supply [1–6]. The generation of coal is accompanied by the production of methane, which is an efficient and clean energy source [7, 8]. The calorific value of 1 m^3 methane is equivalent to 1.21 kg of standard coal, and its combustion does not produce exhaust gases [9]. Although it is a highly efficient energy source, methane is also a greenhouse and explosive gas. The existence of gas seriously restricts the safe production of coal mines. Gas controlling during coal mining is one of the key points for the mining production and management safety, which is also an issue that has to be addressed [10–14]. In 2021, China suffered six coal and gas outburst accidents, in which more than twenty workers were killed. Methane extraction can not only weaken the danger of coal mining but also obtain clean energy and reduce environment pollution [15].

Scholars have carried out theoretical and practical researches on gas extraction technology and method. In terms of extraction borehole placement and optimization, An et al. studied directional boreholes for gas extraction from upper and lower adjacent beds, which broadened the

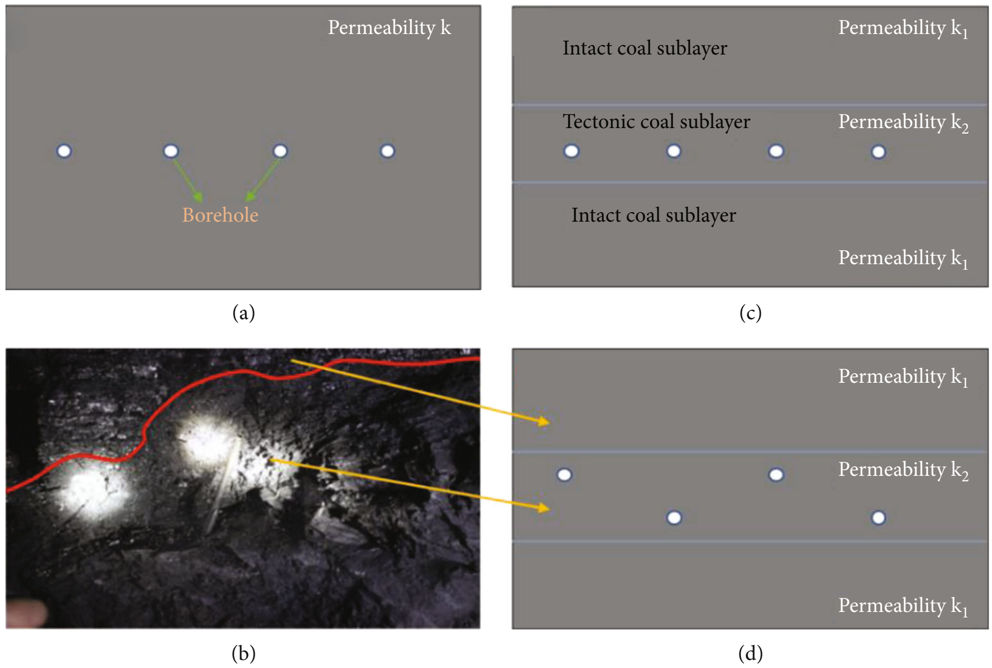

Figure 1: Schematic diagram of coal seam borehole layout: (a) traditional bedding boreholes in a single coal seam; (b) intact and tectonic coal sublayers; (c) bedding boreholes in combined coal seams; (d) adjusted bedding boreholes in combined coal seams.

areas of application of directional boreholes [16]. By conducting on-site high-level drilling field tests, Zhao et al. optimized the parameters of the high-level boreholes based on specific advancing speeds, which ensured production safety and efficiency of the mining working face [17]. A dual-porosity model was constructed by Si et al. to describe gas migration in coal seams, and the ratio of gas diffusion and seepage was used to determine the optimal boreholes distance [18]. After comparing multiple methods of gas recovery in the unloading zone of the extraction area, Li et al. believed that oversized diameter top directional boreholes have a better gas extraction effect [19]. Considering the rapid decrease in gas extraction concentration, a bag-type borehole sealing device was developed by Hu et al. to enhance the methane drainage concentration by cutting off the air leakage loop [20]. The injection of other gases is also an effective way to improve the efficiency of gas extraction. Li et al. found that injecting carbon dioxide into coal seams will displace methane and more carbon dioxide can be adsorbed onto the coal, leading to increased desorption of methane and gas extraction amount [21]. Nitrogen injection tests were conducted by Lin et al. to improve gas drainage in carbon dioxide rich seams. The tests demonstrate that nitrogen injection can significantly improve gas drainage efficiency [22]. Besides, gas diffusion coefficients and mobility are the key factors that affect the extraction efficiency. Zhu et al. found that a higher temperature can increase the gas molecular diffusion coefficients to promote gas extraction [23]. A gas wettability alteration (GWA) technology was used by Jia et al. to increase the fluidity of methane, which can improve the gas extraction efficiency [24].

Above researches have contributed to the improvement on gas extraction theory and technology, but most of the previous studies focus on a single coal seam, and the permeability is usually considered to be consistent throughout the whole coal seam. In engineering, the bedding boreholes are usually constructed in the middle of the coal seam for extraction (see Figure 1(a)), which can maximize the influence of borehole area. However, the formation of coal is accompanied with geological movements. When the coal seam is affected by tectonic stress, the original coal seam structure is damaged and resulted in the formation of tectonic coal. Therefore, there may be tectonic coal sublayer in the coal seam (as shown in Figure 1(b)) [25]. The permeability of tectonic coal sublayer is usually lower than that of the intact coal sublayer. For the circumstance of tectonic coal sublayer existing in the middle of two intact coal sublayers, if the traditional extraction boreholes are constructed in the center of the tectonic coal sublayer (see Figure 1(c)), the maximum gas extraction amount may not be obtained. Although this method of extraction ensures the influence area of the borehole, it ignores the influence of low permeability on gas extraction.

This paper investigates the gas transport characteristics and optimal extraction borehole arrangement for the intact and tectonic combined coal seams. The Comsol Multiphysics is used to conduct numerical solution of the gas-solid coupling model of gas migration. The traditional single-row borehole arrangement is adjusted to up and down alternately (see Figure 1(d)). The gas migration mechanism in combined coal seams and the effect of different vertical spacing of adjacent boreholes (defined as VSAB in this paper) on gas extraction amount are investigated. Then, the optimal VSAB can be obtained by choosing the maximum gas extraction capacity. In order to draw a general conclusion to guide the efficient extraction of gas, the quantitative

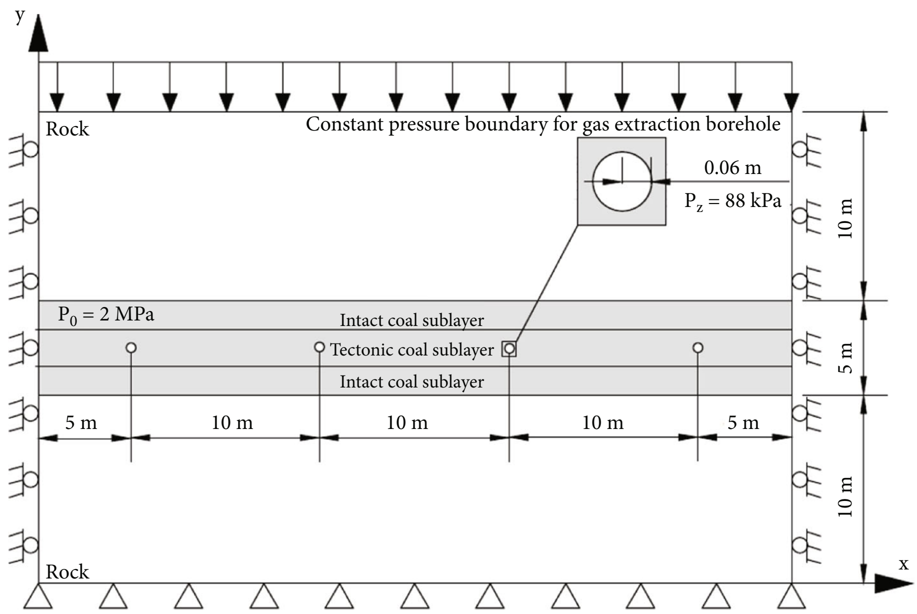

Figure 2: Geometry for gas migration in the combined coal seams.

Table 1: Constant parameters used in the simulation model.

Parameters	Value
Porosity of coal, ϕ	0.06
Density of intact coal sublayers, ρ_{c1}	1449 kg/m^3
Langmuir volume constant of intact coal sublayers, V_{L1}	14.665 cm^3/g
Langmuir pressure constant of intact coal sublayers, p_{L1}	1.115 MPa
Young's modulus of intact coal sublayers, E_1	3380 MPa
Poisson's ratio of intact coal sublayers, ν_1	0.33
Density of tectonic coal, ρ_{c2}	1407 kg/m^3
Langmuir volume constant of tectonic coal, V_{L2}	9.41 cm^3/g
Langmuir pressure constant of tectonic coal, p_{L2}	0.861 MPa
Young's modulus of tectonic coal, E_2	1500 MPa
Poisson's ratio of tectonic coal, ν_2	0.31
Extraction pressure, P_z	88 kPa
Initial gas pressure, P_0	2 MPa
Gas density at standard conditions, ρ_{ga}	0.707 kg/m^3
Molar mass of gas, M_g	16 g/mol
Universal gas constant, R	8.314 J/(mol · K)
Thermodynamic temperature, T	293 K
Dynamic viscosity of gas, μ	1.1067×10^{-5} Pa · s
Module of pore bulk, K_c	307 MPa
Maximum sorption-induced volume strain, ε_L	0.025

relationship between coal seam permeability, coal sublayer thickness, and the optimal VSAB is further investigated. Finally, we propose how to realize the arrangement of combined coal seam dislocation boreholes in engineering.

2. Mathematical Model and Numerical Simulation

2.1. Governing Equations

2.1.1. Gas Seepage Control Equation. The gas flow continuity equation is [26]

$$\frac{\partial X}{\partial t} + \nabla \cdot \left(\rho_g q_g\right) = Q_s, \quad (1)$$

where ρ_g is the gas density, kg/m^3; q_g is the gas seepage velocity, m/s; Q_s is the coal seam gas source, kg/m^3; and X is the coal seam gas content, kg/m^3, which is expressed as [26]

$$X = \rho_g \phi + \rho_{ga} \rho_c \frac{V_L p}{p + p_L}, \quad (2)$$

where ρ_{ga} is the gas density at standard atmospheric pressure, kg/m^3; ρ_c is the density of coal, kg/m^3; V_L is the Langmuir volume constant, cm^3/g; p_L is the Langmuir pressure constant, MPa; and ϕ is the porosity of coal.

According to the ideal gas equation of state, the gas density is expressed as [26]

$$\rho_g = \frac{M_g}{RT} p, \quad (3)$$

Table 2: Numerical simulation schemes.

Case	Thickness of intact coal sublayer H_1 (m)	Thickness of tectonic coal sublayer H_2 (m)	Permeability of intact coal sublayer k_1 (mD)	Permeability of tectonic coal sublayer k_2 (mD)	Permeability ratio (k_1/k_2)	Thickness ratio (H_2/H_1)
1	1.5	2.0	0.02	0.01	2	1.33
2	1.5	2.0	0.02	0.005	4	1.33
3	1.5	2.0	0.02	0.0033	6	1.33
4	1.5	2.0	0.02	0.0025	8	1.33
5	1.5	2.0	0.02	0.002	10	1.33
6	2.0	1.0	0.02	0.005	4	0.50
7	1.8	1.4	0.02	0.005	4	0.78
8	1.2	2.6	0.02	0.005	4	2.17
9	1.0	3.0	0.02	0.005	4	3.00

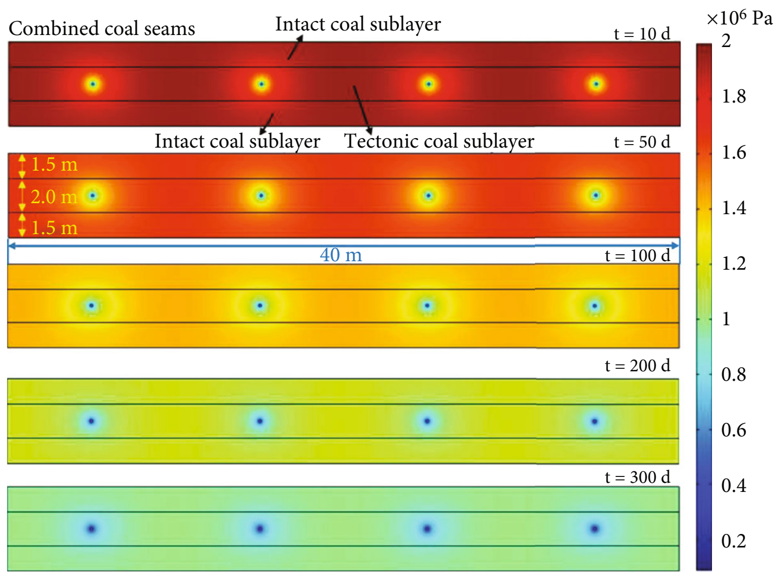

Figure 3: Gas pressure distribution at different extraction times.

where M_g is the molar mass of gas, g/mol; R is the universal gas constant, J/(mol·K); and T is the thermodynamic temperature, K.

The gas seepage is assumed to be laminar flow and follows Darcy's law as [27]

$$q_g = -\frac{k}{\mu}\nabla p, \tag{4}$$

where k is the permeability of coal seam, mD; μ is the viscosity of the gas, Pa•s; and ∇p is the gas pressure gradient, Pa/m.

Equations (2)–(4) make up the gas seepage control equation:

$$\left[\phi + \frac{p_a \rho_c V_L p_L}{(p+p_L)^2}\right]\frac{\partial p}{\partial t} + p\frac{\partial \phi}{\partial t} - \nabla\cdot\left(\frac{k}{\mu}p\nabla p\right) = Q_s, \tag{5}$$

where p_a is the standard atmospheric pressure, 0.101 MPa.

2.1.2. Permeability Evolution Model. A typical permeability model is expressed as [28]

$$\frac{k}{k_0} = \exp\left\{\frac{1}{K_c}\left[\frac{1+\nu}{1-\nu}(p-p_0) - \frac{2E}{3(1-\nu)}\varepsilon_L\left(\frac{p}{p+p_L} - \frac{p_0}{p_0+p_L}\right)\right]\right\}, \tag{6}$$

where k_0 is the initial permeability, mD; K_c is the cleat system bulk modulus of coal, MPa; ν is Poisson's ratio of the coal; E is Young's modulus of the coal, MPa; ε_L is the maximum sorption-induced volume strain; and p_0 is the initial methane pressure, MPa.

2.1.3. Coal Seam Deformation. The governing equation for the coal seam deformation consists of a stress equilibrium equation, geometry deformation equation, and stress-strain relation and can be expressed as [29]

$$G u_{i,jj} + \frac{G}{1-2\nu}u_{j,ji} + \alpha p_{,j} + \frac{K\varepsilon_L p_L}{(p+p_L)^2}p_{,j} + f_i = 0. \tag{7}$$

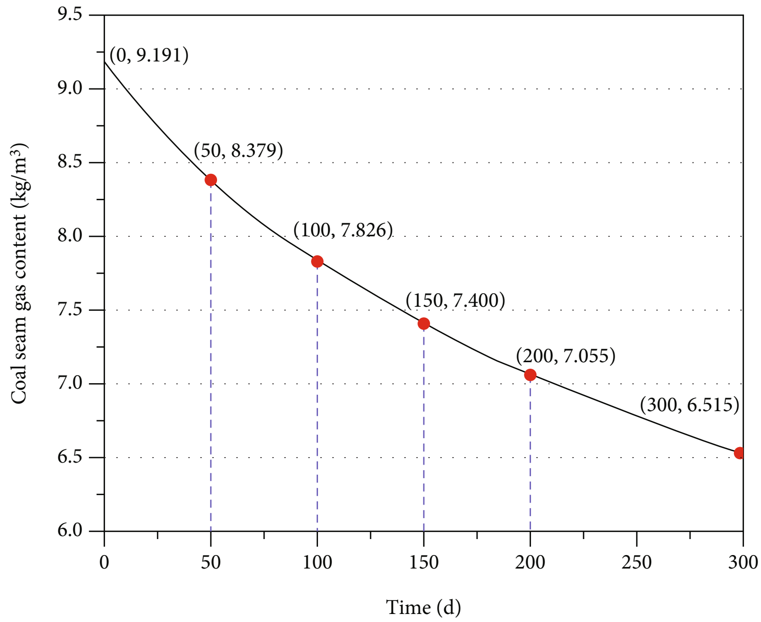

Figure 4: Average gas content of combined coal seams with different extraction times.

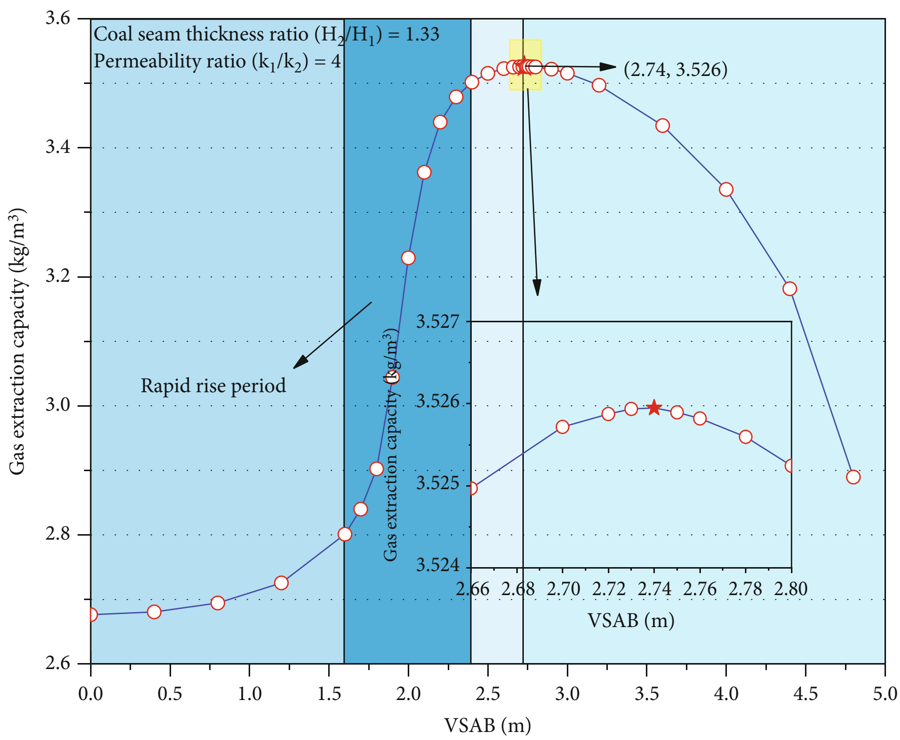

Figure 5: Gas extraction amount of typical combined coal seams (300 d).

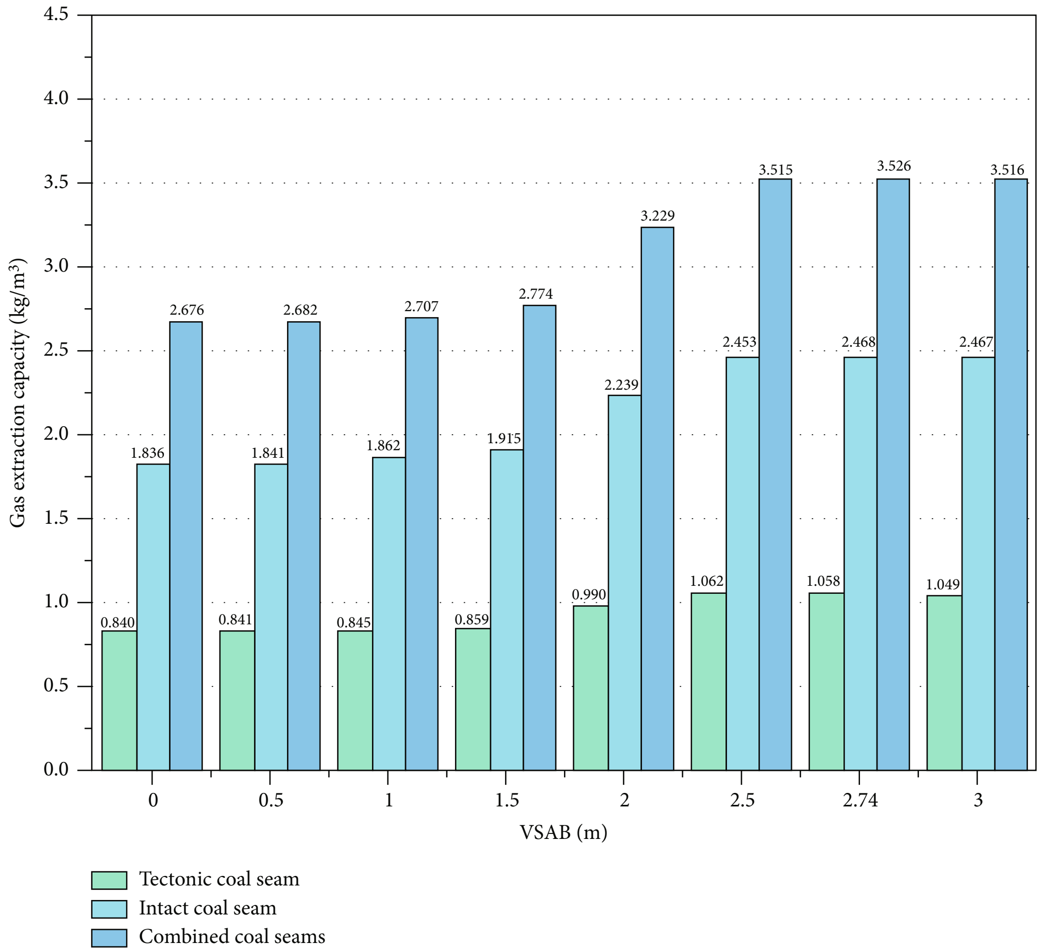

Figure 6: Comparison of extracted gas amount at different VSABs.

2.1.4. Gas-Solid Coupling Model of Gas Migration. Combining Equations (5)–(7), the gas-solid coupling model of methane migration can be obtained:

$$\begin{cases} \left[\phi + \dfrac{p_a \rho_c V_L p_L}{(p+p_L)^2}\right]\dfrac{\partial p}{\partial t} + p\dfrac{\partial \phi}{\partial t} - \nabla \cdot \left(\dfrac{k}{\mu} p \nabla p\right) = Q_s, \\ G u_{i,jj} + \dfrac{G}{1-2\nu} u_{j,ij} + \alpha p_{,j} + \dfrac{K \varepsilon_L p_L}{(p+p_L)^2} p_{,j} + f_i = 0, \\ \dfrac{k}{k_0} = \exp\left\{\dfrac{1}{K_c}\left[\dfrac{1+\nu}{1-\nu}(p-p_0) - \dfrac{2E}{3(1-\nu)}\varepsilon_L\left(\dfrac{p}{p+p_L} - \dfrac{p_0}{p_0+p_L}\right)\right]\right\}. \end{cases} \tag{8}$$

During the methane extraction process, the change in gas pressure will act on the coal seam permeability, and the change of permeability will affect the gas migration velocity and pressure. Thus, Equation (8) becomes the gas-solid coupling model of methane migration, which reflects the gas migration characteristics and the interaction between coal seam and gas.

2.2. Numerical Simulation. Comsol Multiphysics is used to conduct a numerical study on gas extraction in the combined coal seams for 300 days and investigate the influence of different VSABs on the gas extraction amount [30–32]. The geometry conditions of the simulation model are illustrated in Figure 2. The three-dimensional force model is reduced to two-dimensional plane strain model. And the analyzed zone measures 40 m across by 5 m high. Four gas extraction boreholes with radii of 0.06 m are constructed, and the horizontal spacing between adjacent boreholes is 10 m. The left and right sides are roller boundaries, while the bottom is a fixed-end boundary, and the top is a constant load boundary. The borehole extraction pressure is 88 kPa (absolute pressure), and the initial gas pressure is set to 2.0 MPa (absolute pressure).

The constant parameters for the numerical simulation are summarized in Table 1.

To analyze the effects of different coal seam permeability ratios (k_1/k_2) and coal seam thickness ratios (H_2/H_1) on gas migration, the detailed numerical schemes are listed in Table 2.

3. Results and Discussion

3.1. Gas Migration Mechanism of Combined Coal Seams. Numerical simulation case 2 is taken as the typical combined coal seams to analyze the gas migration mechanism. Figure 3 shows the gas pressure distribution at different extraction time (10 d, 50 d, 100 d, 200 d, and 300 d). The gas is

Table 3: Comparison of the gas extraction amount between the traditional and optimal dislocation borehole arrangement.

Different borehole patterns	Gas amount at 100 d (kg/m^3)	Gas amount at 200 d (kg/m^3)	Gas amount at 300 d (kg/m^3)	Time required for gas extraction of 2.50 kg/m^3 (d)
Traditional single-row borehole arrangement	1.326	2.124	2.676	266
Optimal dislocation borehole arrangement	2.013	2.971	3.526	145

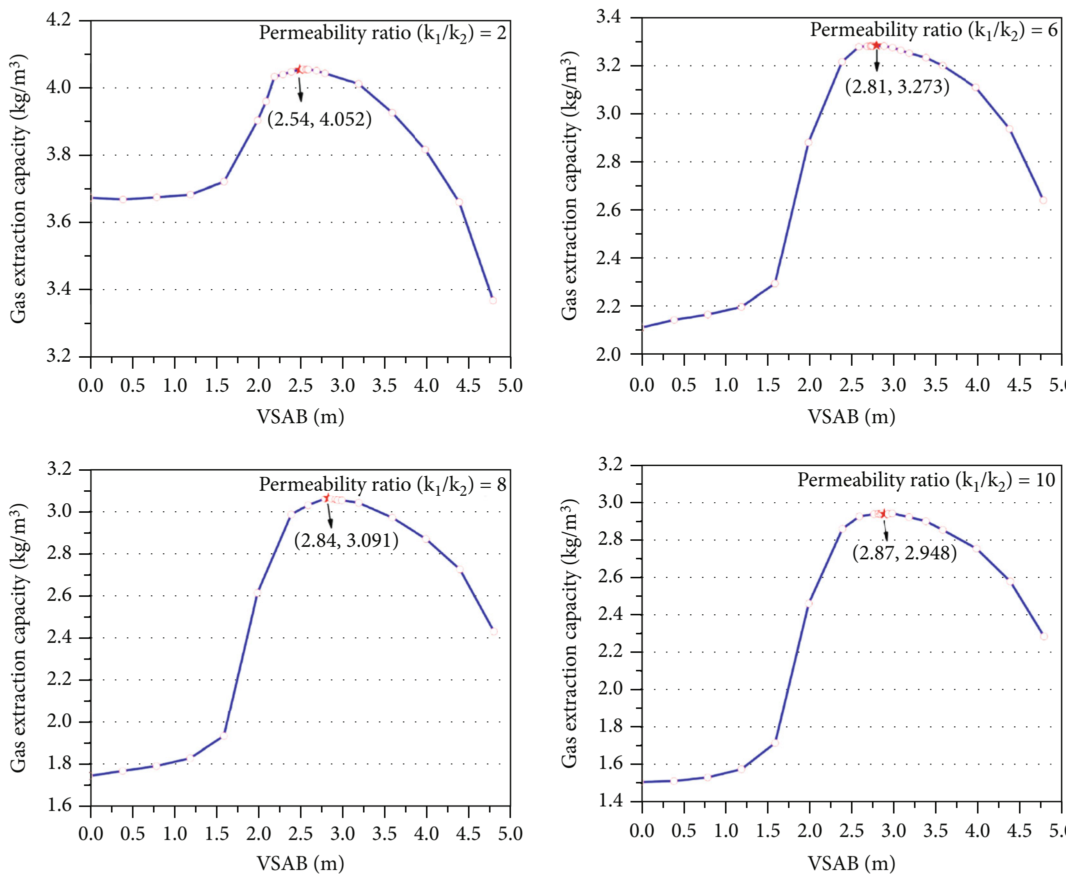

Figure 7: Relationship between gas extraction capacity and VSAB under different coal seam permeability ratios.

influenced by the borehole extraction pressure, and the area of influence extends in a circular pattern from the boreholes to the surrounding area. With the increase of extraction time, the influence area affected by boreholes gradually increases, and the gas pressure gradually decreases. Affected by the extraction pressure, the gas flows from the tectonic coal sublayer to the boreholes, and then, gas in the intact coal sublayers flows through the tectonic coal sublayer into the boreholes as supplementary.

Figure 4 shows the change in the average gas content of the combined coal seams in 300 days. The initial average gas content is 9.191 kg/m^3 (9.191 kilograms of gas per cubic meter of coal). When extracting 300 days, the average gas content decreases to 6.515 kg/m^3. Only 2.676 kg/m^3 of gas can be extracted from the whole coal seam, of which 0.840 kg/m^3 is extracted from the tectonic coal sublayer and 1.836 kg/m^3 from the intact coal sublayers. The reason for the low gas extraction amount is that the tectonic coal sublayer with low permeability restricts the gas to flow from the intact coal sublayers to the boreholes. Therefore, the reasonability of the traditional single-row borehole arrangement of combined coal seams needs to be further discussed.

3.2. Optimal Dislocation Borehole Arrangement in Typical Combined Coal Seams. For the discussion in the previous section, the placement of boreholes in the middle of the combined coal seams may result in the lower gas extraction amount. Thus, the boreholes are adjusted to up and down alternately, and the relationships between gas extraction amount and different VSABs are studied. As can be seen from Figure 5, with the increase in the VSAB, the gas extraction amount first increases and then decreases. When the

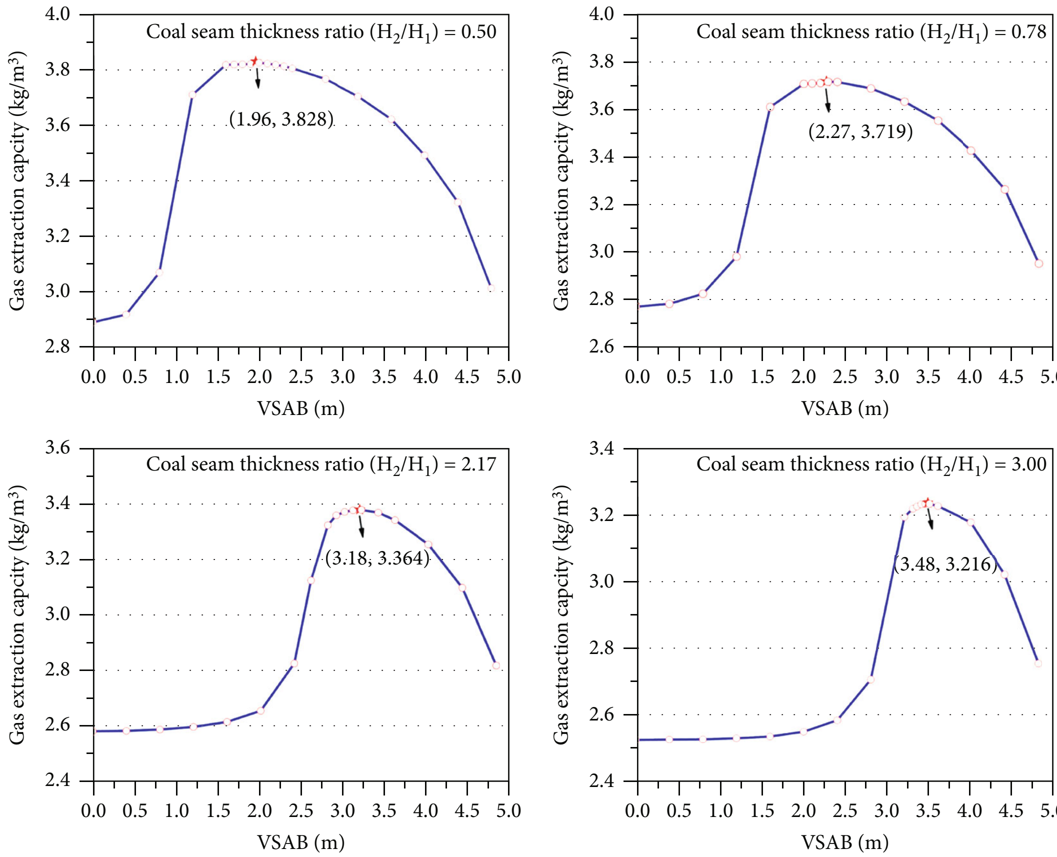

Figure 8: Relationship between gas extraction capacity and VSAB under different coal seam thickness ratios.

Table 4: Comparison of the gas extraction amount under different simulation cases (300 d).

Case	Traditional single-row borehole arrangement for gas extraction (kg/m^3)	Optimal dislocation borehole arrangement for gas extraction (kg/m^3)	Incremental gas extraction amount (%)
1	3.674	4.052	10.3
2	2.676	3.526	31.8
3	2.108	3.273	55.3
4	1.782	3.091	73.5
5	1.533	2.948	91.0
6	2.887	3.828	32.5
7	2.791	3.719	33.2
8	2.578	3.364	30.5
9	2.523	3.216	27.5

VSAB is 2.74 m, the maximum gas extraction amount reaches 3.526 kg/m^3.

To analyze the variation rule and influence factors of gas extraction amount with the VSAB, the gas extraction amount curve can be divided into four parts (see Figure 5).

Curve part 1: in the curve 0–1.6 m interval, the gas extraction amount is small, but the curve is gradually rising. In this part, boreholes are arranged in the low permeability tectonic coal sublayer. As gas is difficult to migrate in the low permeability coal seam, the gas amount extracted from the tectonic coal sublayer is low. With the increases in the VSAB, the boreholes move closer to the intact coal sublayers with higher permeability. As a result, the influence area of boreholes on the intact coal sublayers gradually expands, so the gas extraction amount increases with the increase in the VSAB.

Curve part 2: in the curve 1.6–2.4 m interval, the gas extraction amount grows rapidly. In this period, the boreholes gradually move to the intact coal sublayers with higher permeability. The positive effect on gas extraction keeps growing because gas is easier to flow in the high permeability zone. It should be noted that the influence range of boreholes decreases with the increasing VSAB, which is a negative effect on gas extraction. Overall, the positive effect is

Table 5: Optimal VSAB for different coal seam permeability ratios and coal seam thickness ratios.

Coal seam thickness ratios (H_2/H_1)	Coal seam permeability ratios (k_1/k_2) 2	4	6	8	10
0.50	1.75	1.96	2.04	2.11	2.15
0.78	2.07	2.27	2.35	2.41	2.44
1.33	2.54	2.74	2.81	2.84	2.87
2.17	3.01	3.18	3.24	3.29	3.33
3.00	3.33	3.48	3.54	3.57	3.59

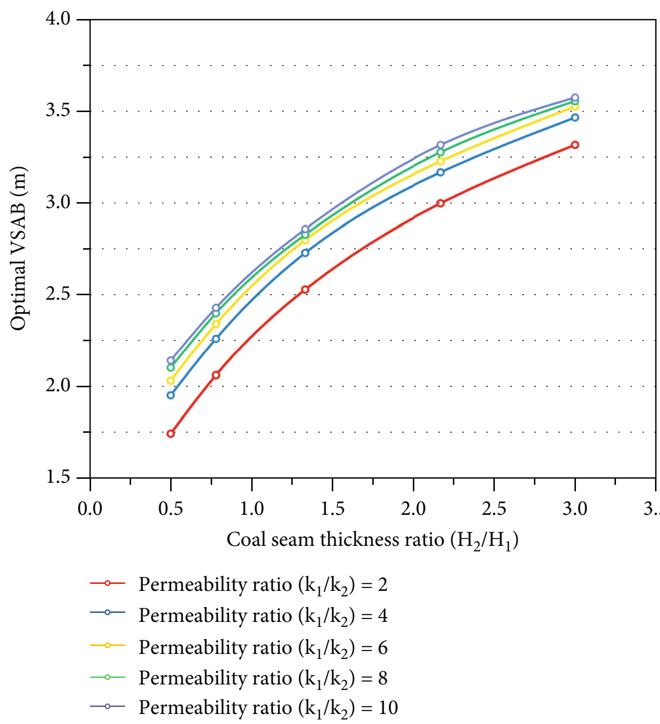

Figure 9: Relationship between optimal VSAB and coal seam thickness ratio (H_2/H_1) for different coal seam permeability ratios (k_1/k_2).

much higher than the negative effect in this period, so the extracted gas amount shows a trend of rapid increase.

Curve part 3: in the curve 2.4–2.74 m interval, the extracted gas amount grows slowly to the maximum value. With the increasing VSAB, the boreholes move away from the center of the coal seam, and the negative effect on gas extraction keeps growing. The gap between the positive and negative effect is narrowing, resulting in a slow increase in the gas extraction amount. Finally, when the VSAB reaches 2.74 m, the maximum gas extraction amount can be obtained with a value of 3.526 kg/m^3.

Curve part 4: in the curve 2.74–4.8 m interval, the gas extraction amount gradually decreases. As the boreholes continue moving towards the boundary of the combined coal seams, the influence area of the boreholes in combined coal seams decreases. In this part, the negative effect is dominant, so the gas extraction amount gradually decreases.

Figure 6 compares the gas extraction amounts of the intact, tectonic, and combined coal seams at different VSABs. When the VSAB is 0 m, the amount of gas extracted from the intact coal sublayers is 1.836 kg/m^3, and the amount of gas extracted from the tectonic coal sublayer is 0.840 kg/m^3. When the VSAB is 2.74 m, the amount of gas extracted from the intact coal sublayers is 2.468 kg/m^3, and the amount of gas extracted from the tectonic coal sublayer is 1.058 kg/m^3. After adjusting the borehole arrangement, gas extraction rates for the intact coal sublayers and tectonic coal sublayer are increased by 34.4% and 26.0%, respectively. Thus, it can be concluded that the dislocation borehole arrangement is beneficial for the gas extraction.

Table 3compares the gas extraction amount of the traditional borehole arrangement with that of the optimal dislocation borehole arrangement at 100 d, 200 d, and 300 d. When the optimal dislocation boreholes are arranged, the extraction rate increased by 51.8%, 39.9%, and 31.8%, respectively. If gas amount of 2.50 kg/m^3 needs to be extracted, the traditional borehole arrangement requires 266 days, while the optimal borehole arrangement can save four months. Therefore, the

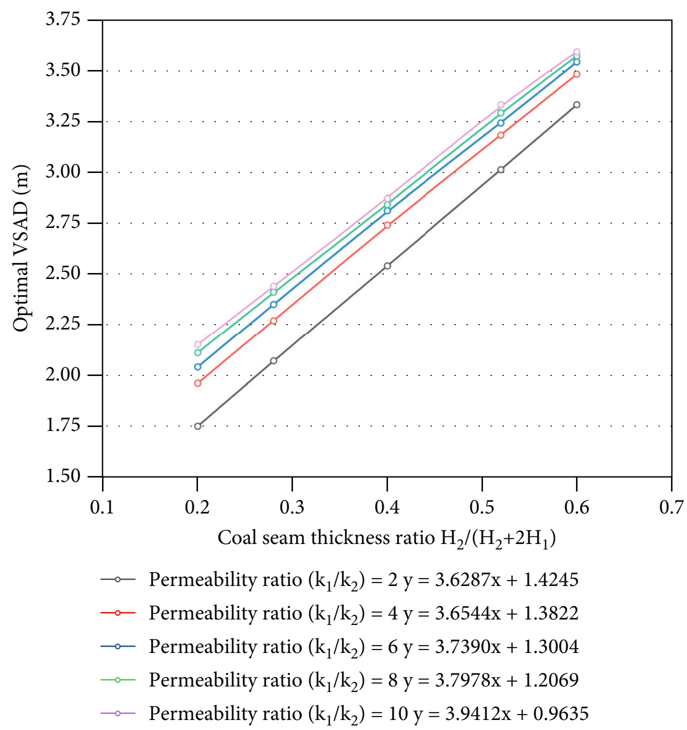

FIGURE 10: Relationship between optimal VSAB and coal seam thickness ratio ($H_2/(H_2+2H_1)$) for different coal seam permeability ratios (k_1/k_2).

dislocation borehole arrangement can greatly increase the gas extraction amount without constructing more extraction boreholes.

3.3. Influence of Coal Seam Permeability on Optimal Dislocation Borehole Arrangement. To investigate the effect of coal seam permeability on optimal dislocation borehole arrangement, cases 1, 3, 4, and 5 in Table 2 are simulated. Figure 7 shows the relationship between the extracted gas amount and the VSAB under the different coal seam permeability ratios (k_1/k_2). When the permeability ratios are 2, 6, 8, and 10, the optimal VSABs are 2.54, 2.81, 2.84, and 2.87 m, and the gas extraction amounts are 4.052, 3.273, 3.091, and 2.948 kg/m^3, respectively. With the increase in the permeability ratio, the optimal VSAB increases gradually and the extracted gas amount decreases gradually. The main reason for this phenomenon is that a higher permeability ratio means a lower permeability of the tectonic coal sublayer with respect to that of the intact coal sublayers. Thus, the boreholes should furtherly move towards the intact coal sublayers, i.e., a higher VSAB value, to enhance the positive effect on gas extraction. Meanwhile, smaller permeability for the tectonic coal sublayer makes it more difficult for gas migration, resulting in a lower gas extraction amount.

3.4. Influence of Coal Seam Thickness on Optimal Dislocation Borehole Arrangement. To investigate the effect of coal seam thickness on optimal dislocation borehole arrangement, cases 6, 7, 8, and 9 are simulated. Figure 8 shows the relationship between the gas extraction amount and the VSAB under the different coal seam thickness ratios (H_2/H_1). When the coal seam thickness ratios are 0.50, 0.78, 2.17, and 3.00, the optimal VSABs are 1.96, 2.27, 3.18, and 3.48 m, and the extracted gas amounts are 3.828, 3.719, 3.364, and 3.216 kg/m^3, respectively. A higher thickness ratio means that the intact coal sublayer is much thinner than the tectonic coal sublayer, so the VSAB value should be larger to reach the optimal extraction effect. Also, a thicker tectonic coal sublayer with low permeability makes it more difficult for gas flow, resulting in a lower gas extraction amount.

3.5. Implications for High Efficiency Gas Extraction. Table 4 summarizes the gas extraction amount and the incremental amount for the traditional borehole and optimal dislocation borehole arrangement. In each case, more gas can be extracted by the optimal dislocation boreholes. The increments of gas amount are 0.378, 0.850, 1.165, 1.309, 1.395, 0.938, 0.928, 0.786, and 0.693 kg/m^3, respectively, and the gas extraction rate increased by 10.3%, 31.8%, 55.3%, 73.5%, 91.0%, 32.5%, 33.2%, 30.5%, and 27.5%, respectively.

Table 5 gives the optimal VSAB for different coal seam thickness ratios and coal seam permeability ratios. When the coal seam permeability ratio is 2 and coal seam thickness ratios are 0.50, 0.78, 1.33, 2.17, and 3.00, the optimal VSABs are 1.75, 2.07, 2.54, 3.01, and 3.33 m, respectively. When the coal seam thickness ratio is 0.50 and the coal seam permeability ratios are 2, 4, 6, 8, and 10, the optimal VSABs are 1.75, 1.96, 2.04, 2.11, and 2.15 m, respectively.

To analyze the numerical relationship between the thickness and permeability ratios and the optimal VSAB, the data in Table 5 are plotted in Figure 9. It can be seen that the optimal VSAB increases with the increasing thickness ratio,

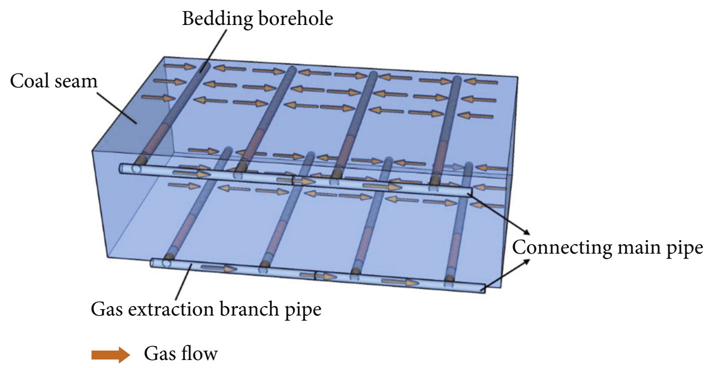

Figure 11: Illustration of dislocation bedding borehole in combined coal seams.

and the growth rate is gradually decreases. The gap between adjacent permeability ratios reduces with the increase in the permeability ratio.

Although Figure 9 shows a satisfying relationship, it is not easy to give the mathematical equations. Then, we set the x-axis to be the thickness of the tectonic sublayer to that of the whole coal seam $(H_2/(H_2+2H_1))$. It can be found that the thickness ratio of the tectonic coal sublayer to combined coal seams has a linear relationship with the optimal VSAB, as shown in Figure 10. The goodness of fit R^2 for each line is over 0.999, which means that the linear fitting is reasonable.

The numerical relationship in Figure 10 can be used to guide the choice of the optimal VSAB. Coal miners should measure the thicknesses and the permeabilities of the intact and tectonic coal, and then, a suitable VSAB can be determined. It should be noted that Figure 10 only shows the optimal dislocation borehole arrangement for combined coal seams with the total thickness of 5 m. The optimal VSAB for coal seam with other thickness should be adjusted appropriately.

In engineering, the optimal VSAB of the actual coal seam can be obtained according to the data relationship in Figure 10, and then, boreholes are constructed in the coal seam. As shown in Figure 11, the boreholes are equally spaced in the horizontal direction and dislocated in the vertical direction, and the vertical spacing between adjacent boreholes is the optimal VSAB. After the completion of borehole construction, branch pipes are used to connect the upper or lower boreholes, respectively, and then merged into the main pipe. In this way, gas can be extracted efficiently using the dislocation borehole arrangement.

4. Conclusions

This paper studies the gas migration characteristics in intact and tectonic combined coal seams. The optimal dislocation borehole arrangements for gas extraction under different thicknesses and permeabilities are discussed. Based on the work completed, major findings are summarized as follows:

(1) In typical combined coal seams, 2.676 kg/m^3 of gas can be extracted in 300 days using traditional single-row borehole arrangement. The low permeability of the tectonic coal sublayer is the main reason for the small gas extraction amount. When the boreholes are adjusted to up and down alternately, more gas can be extracted because of the effect of boreholes on high permeability zones. If the optimal dislocation boreholes with VSAB of 2.74 m are arranged, the gas amount of 3.526 kg/m^3 can be extracted, and the gas extraction rate increased by 31.8%

(2) The optimal VSAB increases when the permeability of the tectonic coal sublayer decreases relative to that of the intact coal sublayer. The optimal VSAB increases when the thickness of the tectonic coal sublayer increases relative to that of the intact coal sublayer

(3) The optimal VSAB increases linearly with the increase of the thickness ratio of the tectonic coal sublayer to the combined coal seams. Coal miners can obtain the optimal VSAB according to the actual coal sublayer thickness, permeability, and numerical relationship in Figure 10 to guide the construction of dislocation bedding boreholes

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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