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Research Article

Network Design Mode of In-Seam Gas Extraction Parameters Using Mathematical Modelling—Take Tangan Colliery as an Example

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Gas extraction is a practical and effective way to guarantee mining-process safety and deliver greater environmental benefits through reducing greenhouse gas emissions and increase the supply of a valuable clean gas resource. It has been effective in recent years, however it still has a series of problems that need to be solved. Gas extraction design mainly relies on engineering experience rather than quantitative design, resulting in low input-output ratio of gas extraction because of unreasonable design. How to build a bridge of communication between engineers and scientists is the key to realize scientific gas extraction. In this work, taking our previous gas-coal and gas-coal-heat coupling models of gas extraction as the theoretical basis, a new communication and design concept—an engineering design platform for gas extraction—is proposed using the network mode. Through the platform, on- and off-line interactions between service centre (scientific workers) and design objects (enterprises or individuals), such as data transmission, material review, scheme design and reviews, and so on. It greatly improves the efficiency and standardization of gas extraction design. Appling the networked platform, the gas extraction engineering parameters were quantitatively designed in the working face of 3307, Tangan colliery. According to the extraction time, the working face was divided into 6 extraction units. The number of boreholes were 763, the drilling capacity of coal was 0.03 m/t, and the extraction rate of each unit was more than 25%. The networked mode of in-seam gas extraction design would transform the traditional experience to the quantitative mode.

1. Introduction

Coal-gas-related accidents including coal-gas outburst and gas explosion always seriously threaten underground mining safety, resulting in large property losses and casualties [1–4]. In recent years, many major coal-gas-related accidents have taken place in China. For example, on October 20, 2004, a serious gas explosion induced by coal-gas outburst occurred in Daping colliery of Henan Province, causing 148 people killed and 32 injured [5]. In order to ensure mining process safety, high levels of gas within the coal should be extracted to a safe limit before exploiting [6, 7]. Gas extraction is not only the fundamental measure to eliminate gas-related disasters and improve the mining safety but also brings valuable environmental benefits: reducing greenhouse gas emissions and provide a source of clean energy and raw materials [8–10]. In 2015, the state administration of work safety issued a document No. 82, which included 10 provisions on strengthening methane control, such as "gas extraction before mining, gas extraction after mining, and gas extraction standard." In 2016, the coalbed methane exploration and development action plan was formulated in the document No. 34 of the national energy administration, and it pointed out that by 2020 the target of underground gas extraction capacity would reach 20 billion m^3 in coal mines and more than 60% utilization rate should be achieved. In-seam gas extraction using the borehole, as the most important technical measure for regional gas disaster control and resource utilization in underground high gas, coal-gas outburst mines, has been widely used[11, 12]. Gas extraction using in-seam boreholes is a complex process involving the multiphysical coupling of gas flow, coal deformation, and temperature transmission[12–16]. Any change or absence of any physical process will affect the opening and progress of another physical process [17–20]. Many scholars have established typical mathematical models to reveal the gas-solid coupling mechanism of coal seam gas flow, such as the Palmer-Mansoori model [21], Shi-Durucan model [22], and Zhang-Liu model [23]. In addition, other models of gas extraction were proposed on the basis of the interaction processes of coal deformation, gas diffusion, and gas flow [23–29]. Furthermore, the evolution law of gas pressure and effective extraction radius in the coal seam was numerically studied through the above models. Considering the rheological characteristics, Hao et al. [30] established a seepage-stress coupling model of gas extraction to reveal the dynamic evolution of coal permeability and gas extraction radius. Based on the gas potential and flow, Wu [31] established a theory model of coal-gas flow to study gas desorption and migration behavior in seam.

In summary, a great progress has been made in multifield coupling models and simulations of in-seam gas extraction. However, less consideration is given to the actual engineering problems on decreasing concentration of gas extraction caused by air leakage around in-seam boreholes (Figure 1), resulting in great deviations between the predicted and the actual results of the gas extraction effect. The conceptualised system of dual-porosity fractured coal abstract coal is shown on the right of Figure 1, which comprises the coal matrix and the coal fractures. The edge dimension of the matrix blocks and the fracture aperture are represented by a and b, respectively, K_n is the fracture stiffness, and σ_e is the effective stress [32]. According to the survey questionnaires in 2012, 62% of predrained concentration decreased to less than 30% in one month, and 66% decreased to less than 16% in two months. To bridge the gap, a fully coupled compositional (coal seam gas and air) model for evaluating the quality of gas extraction was proposed to describe the leakage behavior during gas extraction [32, 33]. Subsequently, we further extended the previous model to evaluate the quality and risk of gas extraction by considering the leakage-induced oxidation heating effect [15].

In fact, although a great success has been made in the gas extraction mechanism, there is still a big gap in the field application because of the limitations of the theoretical level of coal miners. At present, the gas drainage design is unreasonable, which mainly relies on the engineering experience, causing the low input-output ratio in gas extraction, even gas combustion and explosion. In order to solve the above problems, it is an urgent need to build a seamless bridge between workers' skills and scientists. Finally, really let scientific computing play out to the fullest in the field.

2. A Seamless Bridge through Networked Interaction

2.1. Bridge Design and Architecture. How to build a bridge of communication between engineers and scientists is the key to realize accurate gas extraction. Here, a new communication concept—an engineering design platform for gas extraction—is proposed using the network mode. Through the platform, as long as the coal miners give the actual data and requirements, the scientific design scheme of gas extraction will be provided through this platform operated by specialized scientific and technical personnel. The calculation center of the networked platform is mainly based on our previous models of gas extraction, including the coal-gas coupling model [32, 33] and coal-gas-heat coupling model [15]. Derivation and verification of the above mathematical models can be found in our previous work [15, 32, 33]. The idea architecture and calculation models of a seamless communication bridge between engineers and scientists are shown in Figure 2.

It can be observed from Figure 2 that the design objects (coal mine enterprises or individuals) can directly online submit the basic parameter data to the data processing center, including gas occurrence, ventilation, and mining parameters. Subsequently, the center staff will execute the following programs: screening and processing preliminary data, inputting data to the calculation center, evaluating the gas extraction effect under different engineering parameters by simulation, and determining the reasonable extraction mode and parameters. The platform, including the data storage and calculation center, realizes the procedure of data submission, audit, and design online. It enables coal mine enterprises to remotely submit basic data of coal mine, track, and communicate design proposals.

2.2. Design Platform. Based on the network concept of gas extraction, the service platform mainly includes four parts: web browser interface, user module, management and design module, and data storage center. The user module mainly provides the original design data, including project registration, data input, project submission, and project closure checking; the management and design module mainly includes data audit, project distribution, project design and audit, and project submission. The user module, management, and design module mainly interact through the Web browser interface and the data storage center. The design interface of the service platform is shown in Figures 3(a) and 3(b). The main parameters submitted by the project online are shown in Figure 3(c).

The operation process of the service platform includes: (1) the registration and login of new project design objects. (2) Data import, incorporating the profiles of mine and target coal seam, basic parameters of the target coal seam, ventilation parameters of the working face, and gas extraction history of mine or coal seam. (3) Project submission. It mainly refers to the design object submitting the relevant coal mine data to the background data storage center. (4) Project auditing. It mainly refers to the technicians of the design center analyzing the integrity and authenticity of data and realizing the further improvement of the data through the direct return of project or interactive communication. (5) Project distribution. It mainly refers to the managers of the design center distributing the complete data to the relevant project design technicians to complete the design report. (6) Scheme

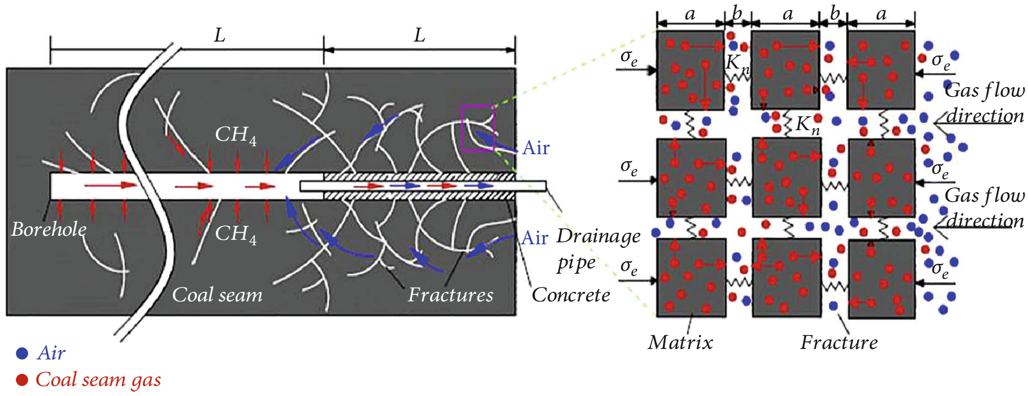


FIGURE 1: Schematic diagram of gas extraction leakage using in-seam boreholes [32, 33].

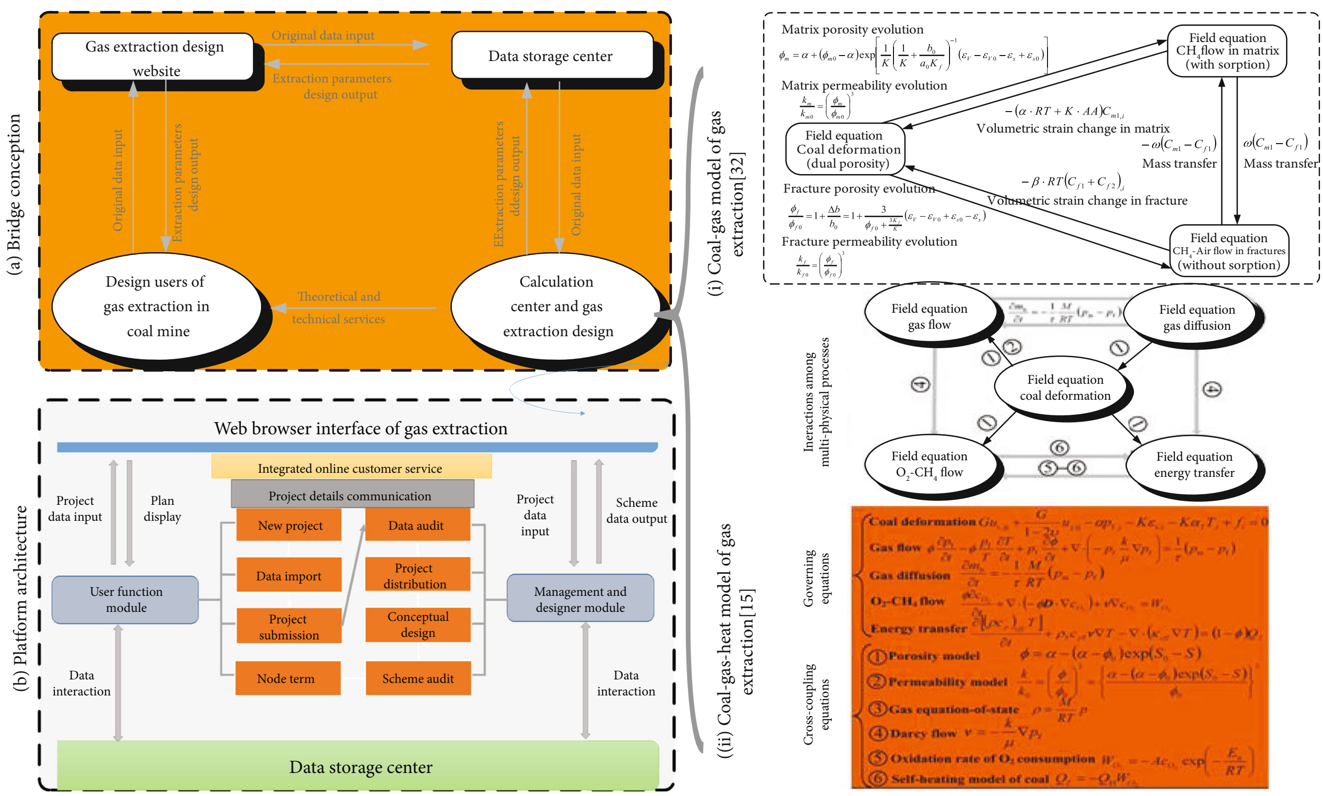
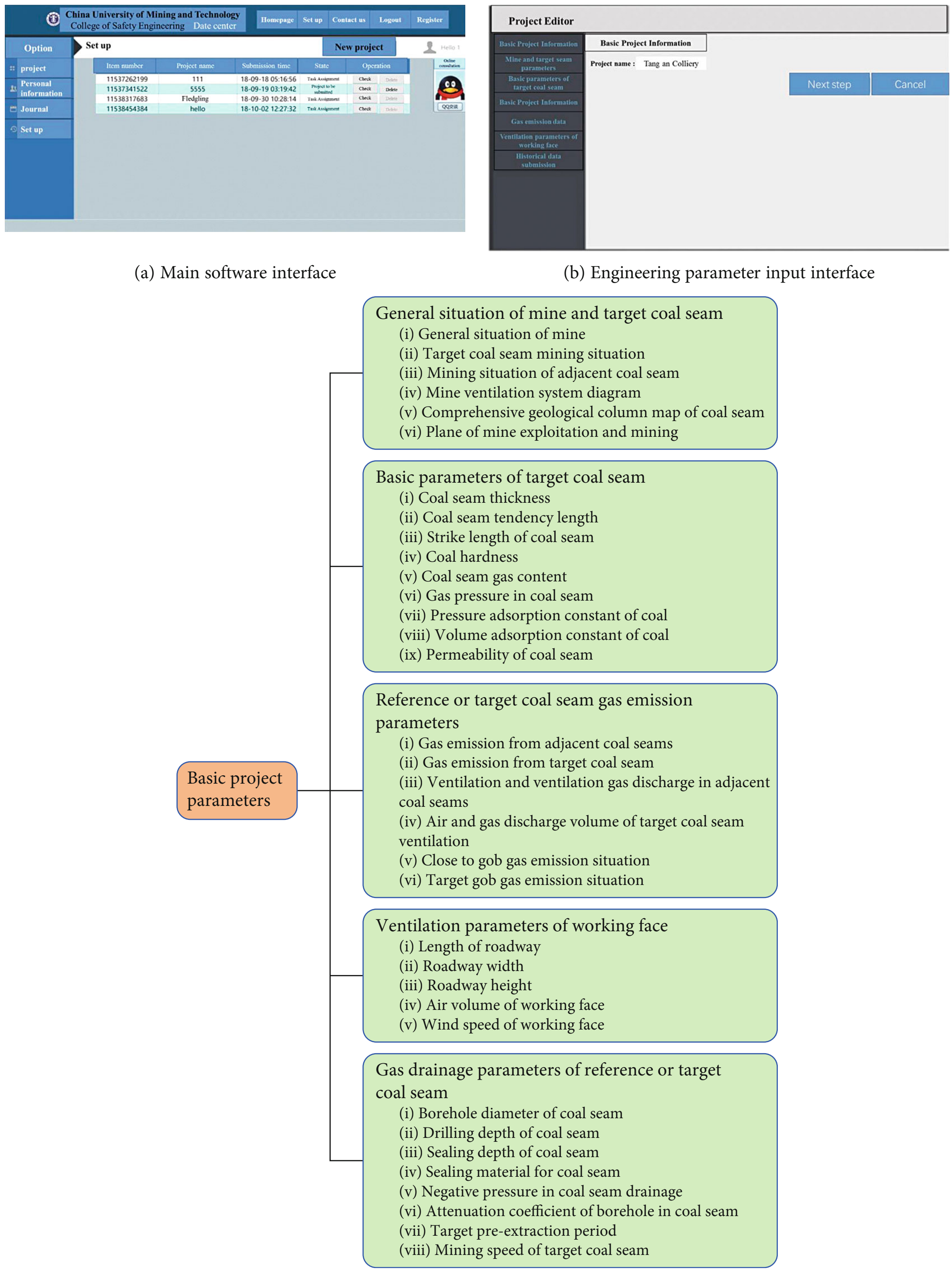


FIGURE 2: Idea architecture and calculation models of engineering design platform.

design. According to the basic information provided by the project, the scheme design technicians can interact on- and off-line through the integration of communication technology with the contact person of the design object to obtain the most complete project basic information. The coal-gas or coal-gas-heat coupling model of gas extraction is applied and solved by COMSOL Multiphysics. Subsequently, the effect of gas extraction under different parameters is evaluated, and reasonable parameters of gas extraction engineering are determined. (7) Plan review. The project management personnel give the pretrial to the design plan of the project. After the pretrial result is ok, the relevant experts are further invited to conduct the plan demonstration of the project design. (8) Project closure. The final design report will be submitted after the examination and approval, including the design basis of the gas extraction project, the prediction method of extraction effect, and the design drawing of gas extraction parameters. (9) Tracking service of scheme. The networked information of measured field data is stored to provide the data analysis basis for the subsequent verification and optimization of the gas extraction scheme.

3. Engineering Examples

3.1. General Situation. Tangan colliery in Shanxi Lanhua Sci-Tech Venture Co. Ltd. (Figure 4) is a high gas mine. Based on



(a) Main software interface

(b) Engineering parameter input interface

(c) Main project parameter input category directory

FIGURE 3: Design interface and main parameters of the service platform.

the network design platform of gas extraction, the basic data of Tangan colliery is easily obtained by on- and off-line interactions between service centre (scientific workers) and design objects (enterprises or individuals). The tendency and trend of working face 3307 are, respectively, 230 m and 1426 m. The track lane is 2148 m including the protective coal pillar between 997 m and 1721 m from the open-off cut. The average thickness of the seam is 6.0 m, and the mining height is 3.0 m. According to the prediction result of the mine gas source, the safe mining of the working face of 3307 needs to

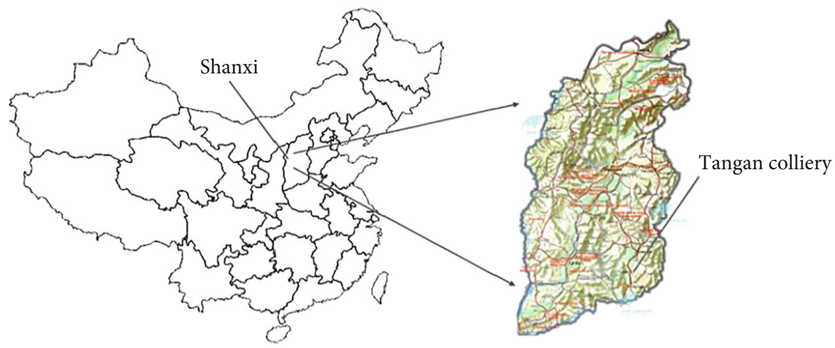


Figure 4: The location of Tangan colliery.

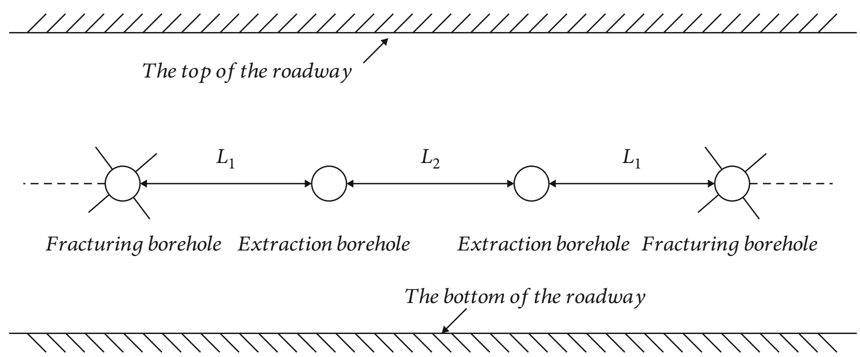


Figure 5: The scheme of fracturing borehole layout.

Table 1: Main parameters of gas extraction simulation.

Parameter	Value
Young's modulus of coal (E, MPa)	3950
Young's modulus of coal skeleton (E_s, MPa)	11850
Poisson's ratio of coal (v, —)	0.4
Density of coal (ρ_c, kg/m^3)	1390
Initial porosity of coal seam (φ_0, —)	0.0137
Initial permeability of coal seam (k, m^2)	5×10^{-17}
Dynamic viscosity coefficient of gas (μ, N · s/m^2)	1.227×10^{-5}
Universal gas constants (R, J/(mol · K))	8.314
Gas molar mass (M, g/mol)	16
Coal temperature (T, K)	300
CH_4 Langmuir pressure constant (p_L, MPa)	0.96
CH_4 Langmuir volume constant (V_L, m^3/kg)	0.035
CH_4 Langmuir volumetric strain constant (ε_L, —)	0.02295
Atmospheric pressure under standard conditions (p_a, MPa)	0.1

meet the residual gas content less than 6 m^3/t. In order to improve the efficiency of gas extraction, liquid CO_2 blasting cracking technology is proposed to increase the effect of gas extraction. The scheme of cracking is to construct a fracturing borehole in every two extraction boreholes (as shown in Figure 5). The basic parameters of gas extraction in the working face of 3307 are listed in Table 1.

3.2. Scheme Design

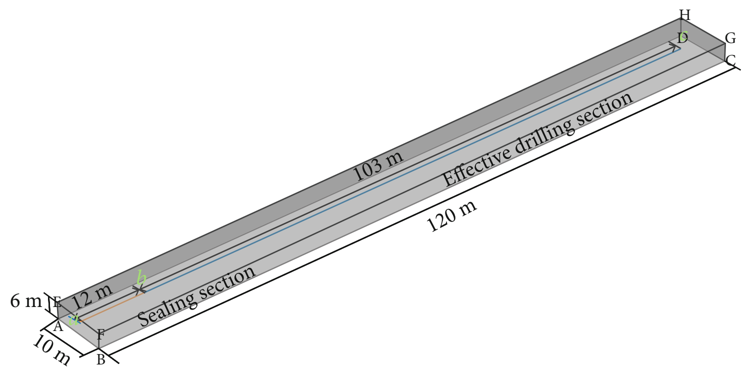
3.3. Division of Extraction Units. Assuming that the extraction unit 1 of the working face is farthest from the open-off cut, its preextraction time t^1_{mean} of boreholes can be estimated as:

$$t^1_{\mathrm{mean}} = \frac{L^1_{\max} + L^1_{\min}}{2u}, \quad (1)$$

where u is the advancing speed of the working face; $L^1_{\max}$ and $L^1_{\min}$ are the farthest and nearest distance between the borehole and open-off cut in the extraction unit 1.

Table 2: Division of extraction units and preextracted time in the working face.

Extraction unit	1	2	3	4	5	6
Distance from open-off cut/m	2100~1670	997~696	696~491	491~345	345~242	242~0
Predrained time	350	242	169	119	83	58



(a) Physical model

Condition		Coal deformation		Gas flow	
		Displacement	Stress	Gas	Air
Initial value		$u_{ij} = 0$	$\sigma_{ij} = 0$	$p_1(0) = 0.28$ MPa	$p_2(0) = 0$ MPa
Boundary conditions	ABEF	$u_x = u_y = 0$	$\sigma_{ij} = 0$	$p_1 = 1$ atm	$p_2 = 1$ atm
	EFGH	$u_x = u_y = 0$	$\sigma_z = -5$ MPa	No seepage	No seepage
	ABCD	$u_{ii} = 0$	$\sigma_{ij} = 0$	No seepage	No seepage
	AEHD, HDCG, BFGC	$u_x = u_y = 0$	$\sigma_{ij} = 0$	Symmetric	Symmetric
	ab	$u_{ii} = 0$	$\sigma_{ij} = 0$	No seepage	No seepage
	bc	$u_{ii} = 0$	$\sigma_{ij} = 0$	$p_1 = 1$ atm $- 40$ kPa	$p_1 = 1$ atm $- 40$ kPa or $-n\cdot\left(-\frac{k}{\mu}\nabla p_2\right)=N_0$

(b) Initial and boundary conditions

Figure 6: Physical model of gas extraction borehole and its initial boundary conditions.

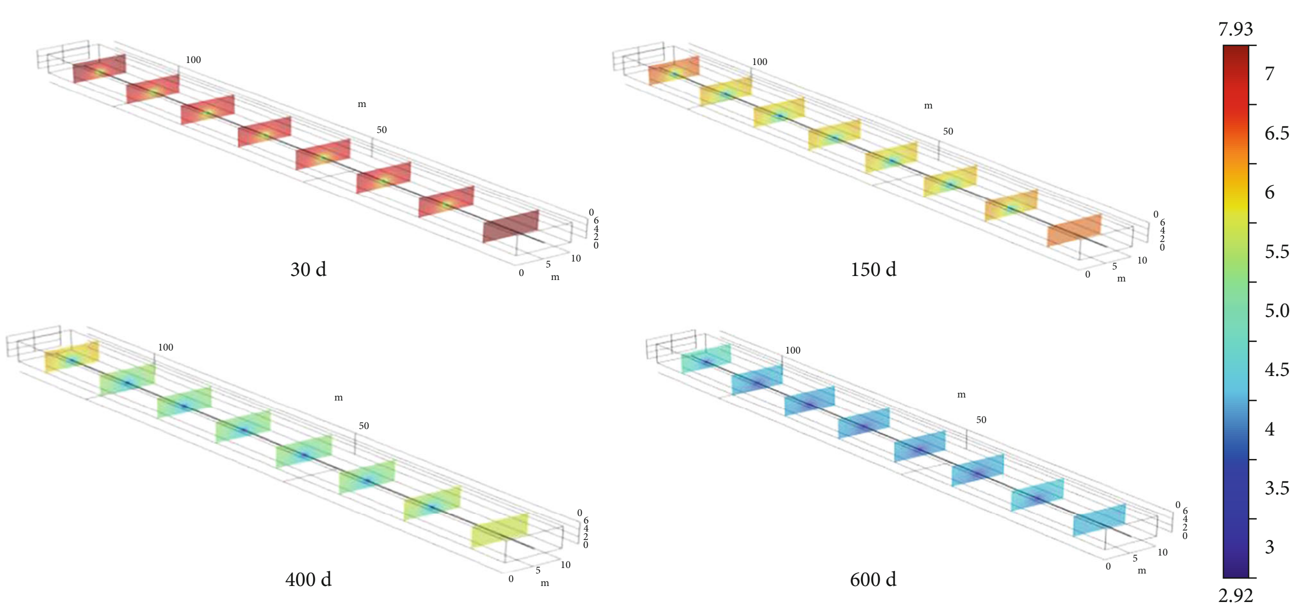
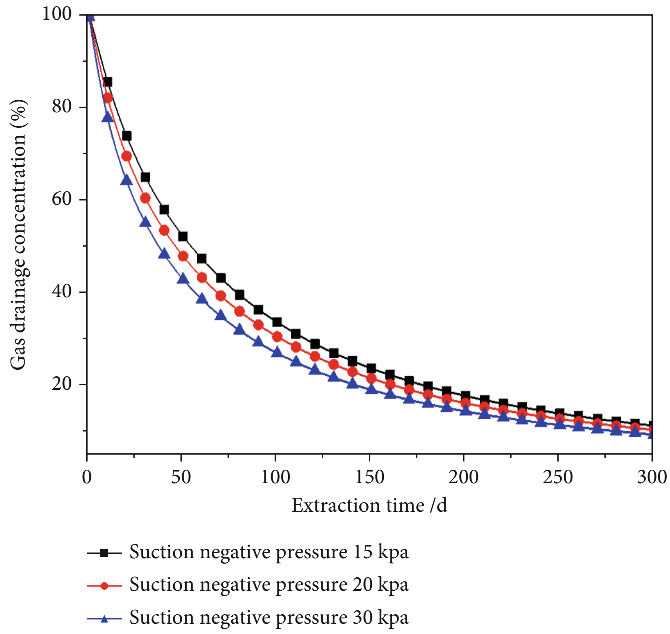
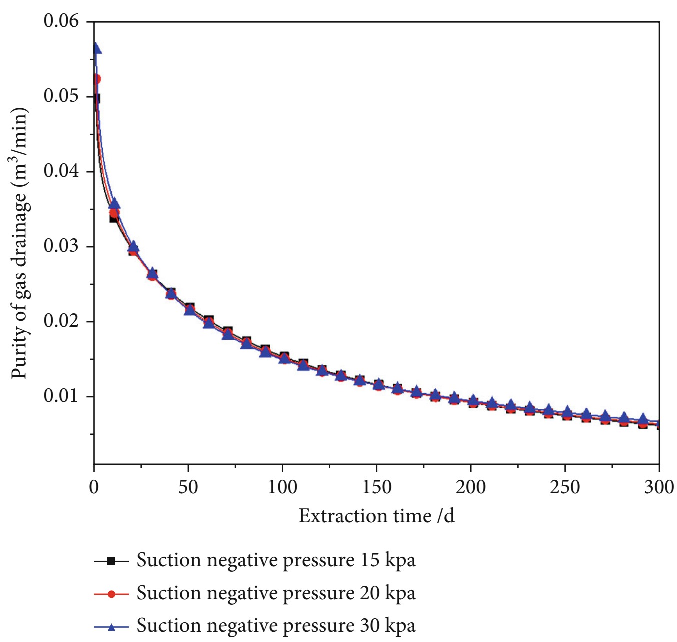


Figure 7: Vertical section diagram of gas content distribution in coal seam with time.



(a) Gas concentration



(b) Pure volume

Figure 8: Variation of gas concentration and pure volume with time under different pressures.

Suppose the farthest and shortest distances between the borehole and open-off cut in the extraction unit i (i>1) are, respectively, $L^i_{\max}$ and $L^i_{\min}$, and the longest and nearest preextraction time are $t^i_{\max}$ and $t^i_{\min}$, respectively. The following relationships can obtain:

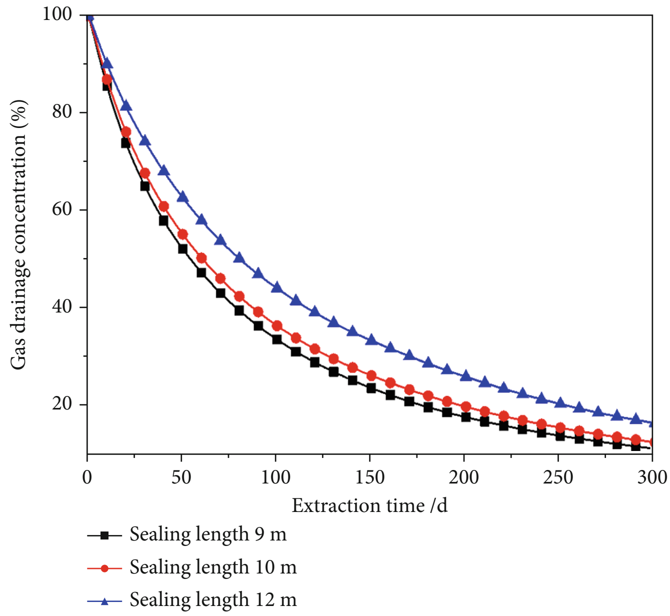
$$\begin{cases} t^i_{\max} = \dfrac{L^i_{\max}}{u} = \dfrac{L^{i-1}_{\min}}{u}, \\ t^i_{\min} = (1-\vartheta) \cdot t^i_{\max}, \\ L^i_{\min} = t^i_{\min} \cdot u, \end{cases} \quad (2)$$

where ϑ is the difference coefficient of preextraction time under the same gas preextraction effect evaluation unit and the value is 0.3.

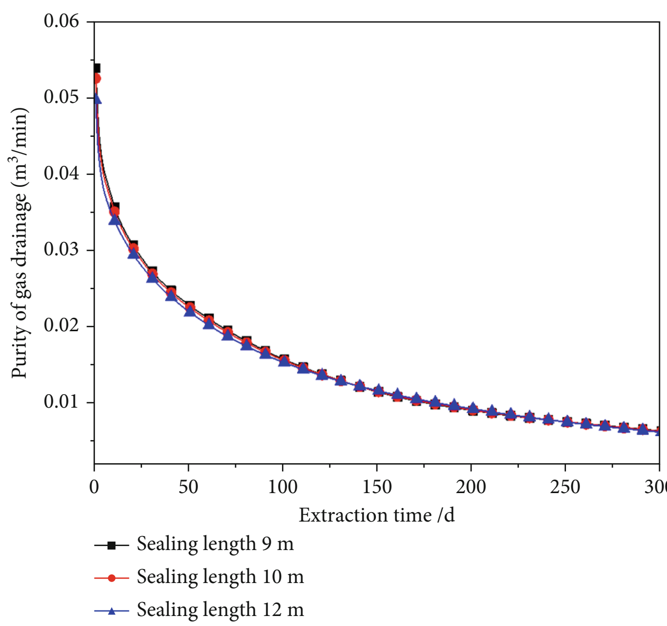
Therefore, the preliminary design time of gas extraction t^1_{mean} is:

$$t^i_{\text{mean}} = \frac{1}{2}\left(t^i_{\max} + t^i_{\min}\right). \quad (3)$$

Based on the above division principle of gas extraction units, the division of extraction units in the working face of 3307 is listed in Table 2.



(a) Gas concentration

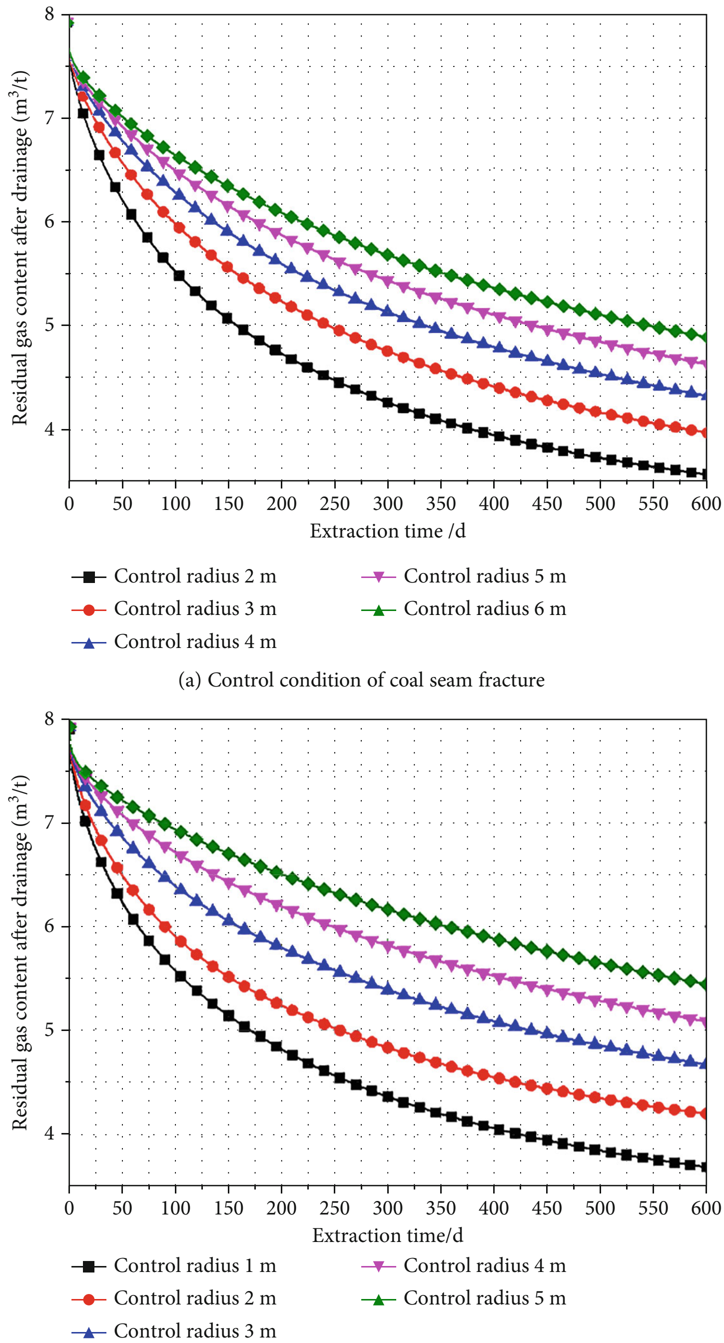


(b) Pure volume

Figure 9: Variation of gas extraction concentration and pure volume with sealing length.

3.3.1. The Influence of Extraction Parameters on Gas Extraction. According to the inclination length of working face and the thickness of coal seam, the length of the borehole is 115 m, the diameter is 113 mm, and the height of borehole is 1.9 m. The physical boundary of gas extraction is shown in Figure 6, and the distribution of gas content in coal seams within 30, 150, 400, and 600 days is shown in Figure 7. It can be seen from Figure 7 that the gas content in coal seam decreases gradually with time. For example, the gas content in most areas of the coal seam decreases to less than 6 m^3/t after 400 days.

3.3.2. Negative Pressure. The variation of gas extraction concentration and pure volume are calculated under different negative pressures of 15 kPa, 20 kPa, and 30 kPa, respectively. As can be seen from Figure 8, both the gas extraction concentration and the pure gas extraction volume decrease with the time. The concentration of gas extraction decreased faster with the increase of negative pressure. However, the pure gas extraction volume was basically the same under negative pressure of extraction, and the negative pressure was selected to be 15 kPa according to the extraction condition.



(a) Control condition of coal seam fracture

(b) Noncontrol condition of coal seam fracture

FIGURE 10: Residual gas content variation with time under different control radius and measures.

(1) Sealing Length. The variation of gas extraction concentration and pure volume with time under different sealing length is shown in Figures 9(a) and 9(b). It shows that when the length of sealing borehole is 12 m, the gas extraction concentration of borehole is obviously higher than that of sealing 9 m and 10 m, while the pure volume of gas extraction is basically the same as that of sealing 9 m and 10 m. Therefore, the length of sealing borehole should be 12 m or more.

3.3.3. Borehole Spacing. The variation of residual gas content with time is in Figure 10 under different control borehole radius and its treatment measures. According to the prediction of gas drainage effect, when the gas content in coal seam is less than 6 m^3/t, it can be defined as the effective control radius of borehole from the borehole edge to the gas content point of less than 6 m^3/t. The borehole spaces of L_1 and L_2 (shown in Figure 5) for each extraction unit are corrected as:

$$\begin{cases} L_1 = 2(r_1 + r_2)e^{-0.139(r_1+r_2)}, \\ L_2 = 4r_2 e^{-0.139(r_1+r_2)}. \end{cases} \tag{4}$$

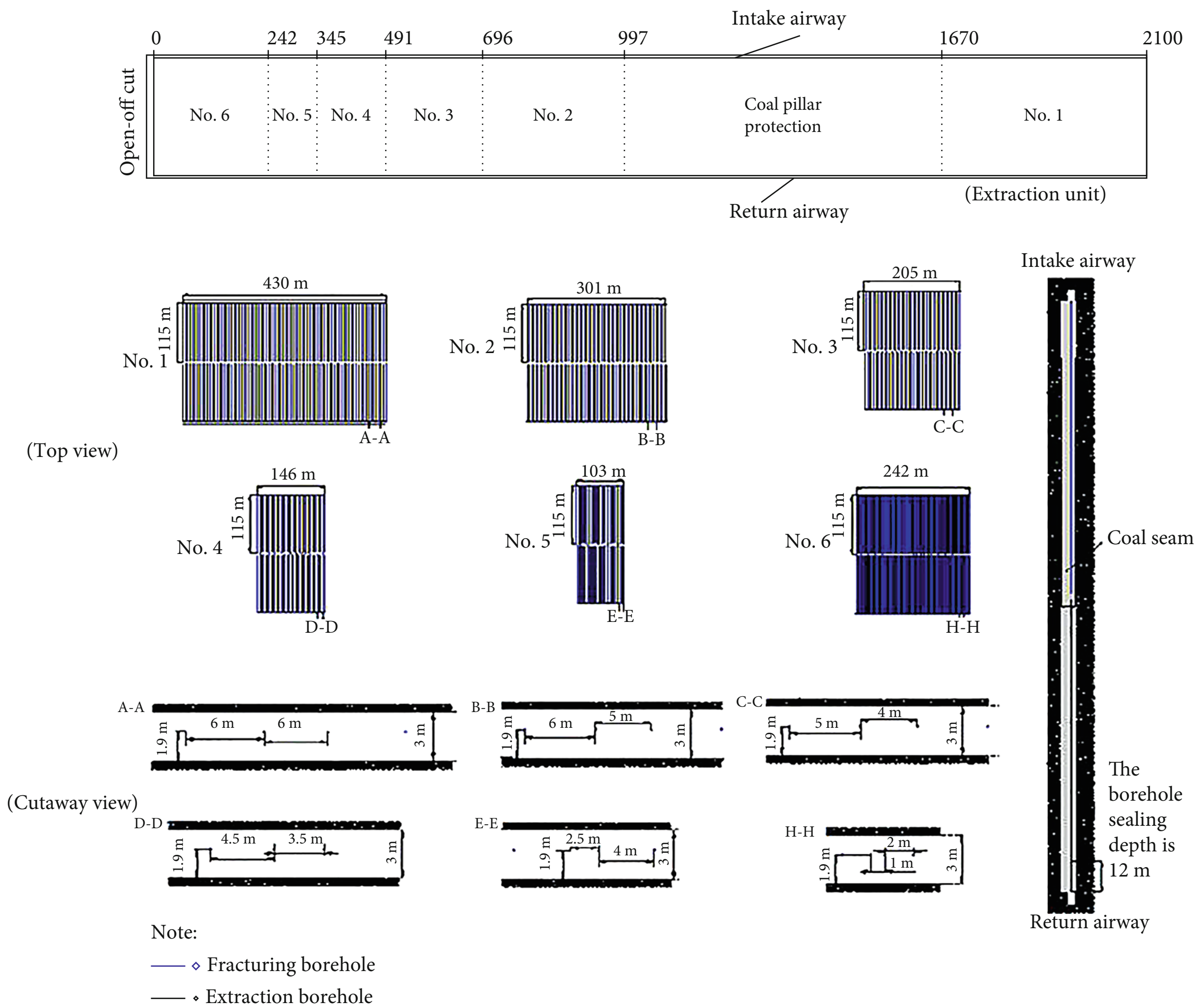


Figure 11: Design drawing of gas extraction borehole along the working face of 3307.

Table 3: Gas drainage effect of each extraction unit in working face 3307.

Extraction unit	1	2	3	4	5	6
Area length/m	430	301	205	146	103	242
Extraction time/d	350	242	169	119	83	58
L_1/m	6	6	5	4.5	4	2
L_2/m	6	5	4	3.5	2.5	1
Number of fracturing boreholes	49	34	30	24	21	97
Number of extraction boreholes	98	67	60	48	41	195
Average pure volume of fracturing borehole/(m^3/min)	0.02	0.023	0.026	0.034	0.04	0.042
Average pure volume of extraction borehole/(m^3/min)	0.019	0.02	0.022	0.027	0.03	0.03
Total extraction volume/($\times 10^7 m^3$)	1.43	0.74	0.51	0.36	0.25	0.83
Gas extraction rate/%	33.50%	26.40%	25.10%	25.00%	25.00%	34.50%

The schematic diagram of extraction engineering parameter design for working face of 3307 is shown in Figure 11. The prediction table of gas drainage effect is shown in Table 3. From Table 3, it can be seen that the gas extraction rate of each extraction unit in this coal seam is more than 25%, which meets the standard requirements.

4. Conclusion

(1) A new communication and design concept—an engineering design platform for gas extraction—is proposed. Through the platform, a series of on- and off-line interactions between service center (scientific

workers) and design objects (enterprises or individuals) can complete, such as data transmission, material review, and scheme design and reviews

(2) Quantitative design parameters of gas extraction can be calculated using our previous gas-coal or gas-coal-heat coupling model. It greatly improves the efficiency and standardization of gas extraction design

(3) Network design mode of in-seam gas extraction parameters using mathematical modelling is applied in the working face 3307 in Tangan colliery. It changes the traditional experience to the quantitative mode of gas extraction design. As a result, both mining process safety and environmental benefits of Tangan colliery get great performance improvement

Data Availability

The data are available on request.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

Acknowledgments

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