Analysis of the Space–Time Synergy of Coal and Gas Co-mining

Bing Qin,* Zhanshan Shi, Jianfeng Hao, Donglin Ye, Bing Liang, and Wei Ji Sun

ABSTRACT: The co-mining of coal and gas is the inevitable future direction of the mining of coal resources. Taking coal mining and gas extraction as the two subsystems of the coal and gas co-mining system, to reveal the mechanism of action between coal mining and gas extraction is the premise of orderly co-mining. On the basis of a similar simulation experiment of coal and gas co-mining, by obtaining the gas migration law during the mining process and collecting a large amount of data on the coal production and gas extraction, it is found that the two subsystems of coal extraction and gas extraction in the coal and gas co-mining system promote and restrict each other. The control parameters for coal mining and gas extraction that affect co-mining are identified. To coordinate the process connection between coal mining and gas extraction, the optimal synergistic relationship of co-mining should be found. The recovery rate and economic benefit of coal and gas resources are taken as the optimization objective function of coal and gas co-mining. Taking the safety production laws, regulations, and production technology-level restrictions of coal mining and gas drainage as constraints, by constituting a nonlinear model for the collaborative optimization of coal and gas co-mining, the method of determining the optimal advancing speed and optimal gas drainage volume of the working face is proposed. By optimizing variables, such as coal mining advancement, coal mining time, gas extraction time, and gas extraction volume, the co-mining of coal and gas is ensured to be safe and efficient, and the output of coal and gas resources is optimized. The time connection and the process succession of the two subsystems are attained. An overall orderly structure is formed between the coal mining system and the gas extraction system, and the mechanism of the cooperative co-mining of coal and gas is revealed. This research has important significance with regard to improving the basic theoretical system of coal and gas co-mining. The control variables of the co-mining working face in the Shaqu mine are optimized. After optimization, the profit is increased by 16.3%, and the gas extraction rate is increased by 2.6%. The drilling spacing is optimized according to the optimization results. The simulation shows that 7 m is the optimal drilling spacing of the working face.

INTRODUCTION

Coal is a very important energy source in the world. For example, China, Poland, the Czech Republic, Australia, and Germany all use coal as their main energy source.1,2 As an associated product of coal, gas extraction can ensure the three effects of coal mining safety, clean energy collection and utilization, and greenhouse gas control.3−5 With the increases in coal mining intensity and mining depth, the gas content is gradually increasing, resulting in difficulty in gas control; the realization of coal and gas co-mining is an inevitable method of coal resource mining.6,7 He et al.8 studied the seepage enhancement and gas drainage effect of the long-distance pressure relief mining of deep high-gas coal seams in the Huainan mining area. Yi et al.9 proposed a concentration-based extraction pressure adjustment method to improve the gas utilization rate. Chen et al.10 and Hao et al.11 established a gas−solid coupling model to study the gas extraction law of the three-dimensional model of a coal seam. Liu et al.12 proposed a theoretical model to describe gas desorption, diffusion, and flow around a drainage hole based on field experimental data. High-level borehole gas drainage is also the main gas control method in complex geological conditions.13 Huijun et al.14 pointed out that the high-level directional deep-hole differential drainage method can effectively control gas emissions in the upper corner of a fully mechanized coal mining face in a thick coal seam. Liu et al.15 studied the influence of the fracture structure on the gas drainage rate under the condition of multifield coupling. Sun16 found suitable coal seam occurrence conditions and mining technology for gas extraction technology through the reasonable arrangement of boreholes. Yang17 conducted research on the complete set of gas drainage
technologies of boreholes for long bedding in coal mines. Zhang et al.\textsuperscript{18} proposed hydraulic punching technology, which significantly improved coal seam permeability and gas drainage efficiency. Qian\textsuperscript{19} carried out research on multidirectional gas drainage technology in the goaf of a working face. Yang\textsuperscript{20} carried out research on the reasonable hole arrangement parameters of surface drilling gas production technology. However, it is difficult to popularize surface combined gas drainage.

Ying\textsuperscript{21} and Li et al.\textsuperscript{22} pointed out that the most effective way to improve the utilization rate of coal mines and reduce greenhouse gas emissions is the co-mining of coal and gas. With the continuous practice of coal and gas co-mining technology, engineers and technicians constantly use the stress redistribution law of the mining process to improve the coal recovery rate and gas extraction rate as much as possible and maximize the mining of the two resources. Therefore, aiming at the co-mining of coal and gas, how to optimize the cooperative production capacity of coal production and gas extraction subsystems under the co-mining system of coal and gas has become an important question to answer in order to realize the safe, efficient, and environmentally friendly mining of coal and gas. The concept of the coal and gas co-mining mode has resulted in several stages of theoretical discussion, engineering application, and conceptual assumptions. Three models have been gradually formed: Huainan mode is combined mining based on the pressure relief of the protective layer; Jincheng mode is combined mining based on directional deep-hole; Yangquan mode is combined mining based on cross-layer drilling. It provides a strong direction and motivation for solving the current difficulties and challenges of coal mining.\textsuperscript{23} Ma et al.\textsuperscript{24} deduced the analytical expression of the radius of the antireflection ring of a borehole for the first time, which provided a scientific basis for the design of the borehole parameters of gas drainage in time and space for coal and gas co-mining. Wu et al.\textsuperscript{25} analyzed the influence of the width of the coal seam mining face on the “three zones” of pressure relief gas migration and further improved the theory of coal and gas co-mining. Li et al.\textsuperscript{26} developed a three-dimensional large-scale physical simulation experimental system for coal and gas co-mining, which can carry out physical simulation experiments for the whole mining process. Cheng\textsuperscript{27} revealed the pressure relief mechanism of soft rock protective layer mining and proposed a three-dimensional pressure relief gas drainage method. Li et al.\textsuperscript{28} and Ning et al.\textsuperscript{29} studied the temporal and spatial evolution characteristics of the three-dimensional stress field and the fracture mechanical behavior of the overburden fracture zone under the repeated mining of coal seams. Yuan et al.\textsuperscript{30} established a sequence parameter model of the coal and gas co-mining system with the daily coal production of the working face, the expansion volume of the overburden fracture zone, and the pressure-relieved gas emissions as co-mining variables. The mechanism of the co-mining synergistic variables was revealed. Yuan\textsuperscript{31} analyzed the principle, types and geological conditions of the coal and gas co-mining mode in a protective seam under the condition of a coal seam group. Zhang et al.\textsuperscript{32} pointed out that gob-side entry retention and gas drainage hole stability are two key technologies for the co-mining of coal and gas without coal pillars. Liu et al.\textsuperscript{33} adopted the protective layer mining method to solve the mining problem of deep high-gas-outburst coal seams. Wang et al.\textsuperscript{34} and Liu et al.\textsuperscript{35} established the safety engineering of a three-dimensional gas drainage and utilization system.

The above research results are the specific conditions of co-mining technology that have been used to solve specific technical problems in the process of co-mining coal and gas, but the basic theory matching with co-mining technology has not yet been formed. The co-mining of coal and gas covers two subsystems of coal mining and gas extraction. The complex relationship between the two subsystems that restrict and promote each other is not clear. It is difficult for coal mining and gas extraction to achieve synchronization and coordination in terms of time and process connection, resulting in generally low gas extraction rates. It is necessary to analyze the relationship between the coal mining volume, mining progress, gas extraction volume, extraction time and other co-mining factors, quantitatively evaluate the co-mining effect, and optimize the co-mining parameters to achieve better coal and gas co-mining. At present, there is no relevant research report on the analysis of the co-mining space—time synergy. The author analyzes the influencing factors of coal mining and gas drainage from laboratory experiments, field production data, and theoretical analysis. This paper analyzes the interaction mechanisms among the influencing factors and puts forward an optimal calculation model of coal and gas co-mining, which establishes a theoretical model for realizing an orderly connection between coal mining and gas extraction and forms the theoretical support of coal and gas co-mining technology, which is rarely reported in the currently published literature. Liang et al.\textsuperscript{36,37} established evaluation indices from two aspects of coal mining and gas extraction, established a coordination evaluation system of coal and gas co-mining, and quantified the effect of coal mining and gas extraction in the mining process of a working face. The basic data are provided for the optimization of the co-mining system. A co-mining optimization model of coal and gas in the working face is established,\textsuperscript{38} which is the prototype of the co-mining optimization calculation model proposed in this paper.

On the basis of the synergetic theory, this paper proposes the idea of optimizing the co-mining system by adjusting the variables of coal and gas co-mining. Self-developed coal and gas co-mining experimental equipment was used to carry out co-mining experiments, and a large number of statistical identifications were carried out on the actual production data. Then, the complex relationship between the two subsystems of coal mining and gas drainage is analyzed. The influence of the control parameters, such as coal mining advancement, gas emission, and gas extraction, on the effect of coal and gas co-mining is revealed. The optimization objective function and constraints of coal and gas co-mining are constructed. Finally, the theory of coal and gas co-mining based on the collaborative optimization mechanism is established. The research results are of great significance for improving the basic theoretical system of coal and gas co-mining.

1. INFLUENCE OF COAL MINING ON GAS FLOW

1.1. Laboratory Experiment on the Influence of Mining on Gas Flow. 1.1.1. Engineering Geology Background. The research objects are the No. 2 coal seam and underlying No. 3 and No. 4 coal seams in the Shuinsu mine. Working face 22201 is located in the No. 2 coal seam. The No. 2 coal seam occurs in the middle of the Shanxi Formation, and the average minable thickness of the coal seam is 1.07 m. The No. 3 coal seam occurs in the middle and lower parts of the
Shanxi Formation, and the average minable thickness of the coal seam is 1.07 m. It does not contain gangue or occasionally contains one layer of gangue, and the structure is simple. The No. 3 coal seam occurs in the lower part of the Shanxi Formation, with an average coal thickness of 2.98 m. It is a stable minable coal seam within the whole mine field. The average distance between the roof of the No. 3 coal seam and the floor of the No. 2 coal seam is 17.7 m. The spacing between the No. 3 and No. 4 coal seams is small, which can be regarded as the same seam. The No. 2201 working face is the first upper protective layer mining experimental working face of the No. 2 coal seam in the North No. 2 mining area. The maximum advancing length of its strike is approximately 1538 m, the inclined direction is 150 m, the average inclination of the coal seam is 2°, and the mining height is 1.6 m. The mining method is inclined longwall retreating comprehensive mechanized mining, and the roof management method of the goaf is the caving method.

The gas drainage design of the No. 2201 working face is shown in Figure 1. A drilling yard is arranged every 50 m on the mining side of the No. 2201 auxiliary transportation roadway and No. 2201 machine rail integrated roadway. A total of 38 drilling yards are arranged, and 8 boreholes are arranged in each drilling yard. A total of 304 boreholes in this coal seam are constructed in the drilling yards of machine rail integrated roadways and auxiliary transportation roadways. A 4-in. pipe is reserved every 9 m in the filling body of the No. 2201 reserved roadway and connected with a flange embedded pipe, extending 0.5 m out of the wall, and each 4-in. pipe is connected with the Φ320 drainage pipe at the nonmining side of the roadway. The nonmining Φ320 drainage pipe is extended to the back of the goaf of the No. 2201 working face to realize gas drainage in the goaf.

1.1.2. Similar Simulation Experiment of Coal and Gas Co-mining. 1.1.2.1. Equipment Introduction. The self-developed coal and gas co-mining experimental device39 is used to carry out a similar simulation experiment of coal and gas co-mining. The main size of the device is 1410 mm × 372 mm × 1120 mm. The experimental device is mainly composed of front and rear main sealing cabins, an overburden rock loading device, a rock stress testing device and data acquisition system, a flow testing device, image acquisition equipment, and a front panel strength reinforcement device. The upper chamber is a flexible loading chamber, which is used for the loading of the overlying stress; the lower chamber is the main part of the experimental device, which is used for the installation of the stress box. Similar models are used for protective layer mining under sealed conditions. The front panel is the observation panel of the experimental device and is used for the flow test of gas in similar materials. Moreover, there is a protective layer mining sealing window on the front panel. The sealing window cover is opened before each mining process, and the sealing window cover is closed after mining for infiltration. During the mining process of the protective layer, the displacement change of the overlying rock and the evolution of the cracks can be observed through the observation window on the front panel; the rear panel is the air inlet panel for the permeability test of a similar model. The structure diagram of the experimental device is shown in Figure 2.

1.1.2.2. Model Matching. The plane strain model was used in the experiment. The similarity constants are shown in Table 1, and similar simulated material ratios are shown in Table 2.

| Similarity Constants | $C_{\text{geometry}}$ | $C_{\text{time}}$ | $C_{\gamma}$ | $C_{\sigma}$ | $C_{K}$ |
|----------------------|-----------------------|-----------------|-------------|------------|--------|
| 1.10                | 10                    | 1.8             | 180         | 5.6        |

1.1.2.3. Data Monitoring and Recording. The purpose of the simulation experiment is to mine No. 2 coal and protect No. 3 + No. 4 coal. The excavation step distance is 5 cm. After each excavation is completed and the rock formation is stabilized, each permeability measuring point is ventilated in turn, and the flow rate test is carried out on each flow

![Figure 1. Design of extraction drilling in the 22201 working face.](image1)

![Figure 2. Similar simulation experiment of coal and gas co-mining.](image2)
measuring point. The gas flow is obtained by the drainage method. The ventilation pressure is adjusted to a uniform value, and the permeability is calculated by flow. During the model paving process, the stress sensor is embedded in the designated position and connected to the strain acquisition instrument through the terminal post of the test bench, and the data of the strain acquisition instrument are automatically saved on the computer. Finally, the changes in the stress and permeability of the measuring points in the whole mining process can be obtained.

To more intuitively reflect the degree of pressure relief, the “pressure relief coefficient” of the coal seam is adopted, which is defined as the ratio of the stress after pressure relief to the initial stress. The relative variation coefficient of permeability is defined as the ratio of the permeability after pressure relief to the initial permeability.

1.1.2.4. Experimental Results. Figure 3 shows the change curve of the stress and permeability of measuring point 4059 (1) in the middle of the No. 3 + 4 coal seam goaf when the working face advances to different distances. This measuring point can reflect the changes in the stress and permeability in the whole process of No. 3 + 4 coal seam pressure relief. Figure 3a shows the change law of the stress of the No. 3 + 4 coal seam under the action of No. 2 coal seam mining. The working face advances in the range of 0–16.7 m, and the stress decreases, 16.7–31.2 m; increased stress, 31.2–60 m stress reduction. Figure 3b shows the permeability change curve of the No. 3 + 4 coal seam. The permeability increases at 0–20 m, decreases at 20–36 m, increases at 36–40 m, and decreases at 40–54 m. The main reason for this is the influence of the two cycles of pressure. In the process of advancing the working face, the stress shows the law of decrease—increase—decrease, and the corresponding permeability increases—decreases—increases, while the permeability of the coal seam changes locally when the mine pressure appears.

1.2. Field Observation of the Influence of Mining on Gas Flow. According to refs 40 and 41 different tracer gases were injected into coal seams on site, and the fracture penetration and pressure relief gas migration of each coal and rock seam during mining in the Shaqu mine working face were observed. SF₆ exists in the gas samples collected in the goaf during the mining of the uppermost No. 2 coal, which indicates that penetrating fractures have been generated between No. 2 coal and the lower No. 3 + No. 4 coal. Helium is collected after further advancing, which indicates that fractures also occurred between No. 5 coal and No. 3 + No. 4 coal, the development time lags behind the fractures of No. 2 coal and No. 3 + No. 4 coal, and the former fracture scale is much smaller than the latter. After the upper protective layer is mined, the pressure of the protected layer is relieved upward, and the shear failure in the coal seam causes the formation of penetrating cracks between layers, which promotes the movement of the gas from the protected layer into the working face. From the perspective of coal seam group mining, the mining action of this coal seam makes the gas from the protected layer gush out to the mining space of the working face. The field observation results verify the similar simulation experimental results of coal and gas co-mining.

1.3. Change in Gas Drainage Volume with Advancing Working Face. Various gas drainage methods are mainly applied in the 22201 working face, such as bedding drilling drainage, high-level drilling drainage in the fractured zone, large-diameter drilling drainage, pressure pipe drainage in the goaf of the working face, and high drainage roadway. According to statistics, the relationship between the advancing distance of the working face and the amount of gas discharged and extracted by wind is shown in Figure 4.

With the advance of the working face, the gas drainage volume of the coal seam shows a downward trend, and there is a large fluctuation before the initial pressure, which is obvious...
in the track roadway. Under the influence of mining, the disturbance in front of the working face produces cracks, the permeability of the coal seam increases, and the drainage volume increases. With further advancement, the drainage volume tends to be stable and then begins to decrease slowly.

In the initial stage of mining, the gas drainage volume of adjacent layers is low. The mining gradually advances, and as the pressure relief range of adjacent layers gradually increases, the gas drainage volume also gradually increases. Then, with the stable advancement of mining, the drainage gradually stabilizes, and there are short-term fluctuations during the periodic weighting period.

After the working face is advanced for 60 m, the buried pipe in the goaf of the retaining roadway starts to drain, and the drainage volume is basically stable at 1 to 1.5 m³/min, which is weakly affected by mining.

2. INFLUENCE OF GAS DRAINAGE ON COAL MINING

2.1. Relationship between Gas Emission and Mining Speed. 2.1.1. The Relationship between Gas Emission and Mining Speed in the Coal Seam. 2.1.1.1. Gas Emission and Mining Speed. 2.1.2. Calculation of Gas Emission in the Adjacent Layer. 2.1.2.1. Calculation of Gas Emission in the Adjacent Layer. According to the calculation formula of the gas emissions from the upper and lower adjacent layers to the mining layer for gas emission, m³/S; \(X_{0i}\) is the volume of gas in units of cubic meters of coal in the \(i\)th adjacent layer, m³/m²; \(m_i\) is the coal thickness of the \(i\)th adjacent layer, m; \(\eta_i\) is the gas emission rate of the \(i\)th adjacent layer, \(\eta_i = (X_{0i} - X_{gi})/X_{0i}\). \(X_{gi}\) is the residual gas content of the \(i\)th adjacent layer, m³/t; and \(c\) and \(d\) are coefficients related to the geological conditions and advancing speed of the working face.

In a mine, through the statistical analysis of data, as shown in Figure 5, when the gushing volume and propulsion degree are within the limit value, the relationship between the two is linear; otherwise, the relationship is parabolic. As the speed of the working face increases, the deformation and destruction of the surrounding rock takes a short time, and the speed slows. In addition, the goaf falls, the range of cracks is reduced, and the openings of the cracks are small, which weakens the gas emission of adjacent layers.

2.1.2.2. The Volume of Gas Flowing into the Goaf from Adjacent Layers. According to the calculation formula of the gas emissions from the upper and lower adjacent layers to the gob proposed by former Soviet scholars, the influence of the advancing speed on the gas emissions from adjacent layers to the gob is as follows:

\[
q_{gyi} = m_i \rho_i L_q v_h (X_{0i} - X_{gi})
\]

The relationship between gas emission from adjacent layers and mining speed during mining can be expressed as

\[
v_{h+1} = q_{by1} \left( dL_q \sum_{i=1}^{n} X_{0i} \eta_i \right)^{-1}
\]

where \(q_{by}\) is the absolute influx of the upper and lower adjacent layers into the mining layer for gas emission, m³/S; \(X_{0i}\) is the volume of gas in units of cubic meters of coal in the \(i\)th adjacent layer, m³/m²; \(m_i\) is the coal thickness of the \(i\)th adjacent layer, m; \(\eta_i\) is the gas emission rate of the \(i\)th adjacent layer, \(\eta_i = (X_{0i} - X_{gi})/X_{0i}\). \(X_{gi}\) is the residual gas content of the \(i\)th adjacent layer, m³/t; and \(c\) and \(d\) are coefficients related to the geological conditions and advancing speed of the working face.
where $q_{ly}$ is the gas emission from the upper or lower adjacent layers to the goaf, $m^3/s$, and $\rho_i$ is the coal density in the upper or lower adjacent layers, $kg/m^3$.

The working face of the Shaqu Mine generally adopts the whole height of mining at one time, so the gas in the goaf mainly comes from the gas influx from the adjacent layers. In the above formula, after the working face layout parameters are determined, the mining speed and the gas emission from adjacent layers also increase linearly. Therefore, whether it is the coal seam, the adjacent layers, or the goaf, there is a certain relationship between the gas emission and the mining speed, and the gas emission varies with the change in mining speed.

2.2. Relationship among Gas Emission, Drainage Volume, Wind Displacement and Mining Speed. From the analysis in subsection 2.1, it can be concluded that in the mining process of the working face, as the mining speed increases, the gas emission increases, and the gas emission decreases. The gas emission is solved by the drainage and ventilation. The upper limit of the gas emission is restricted by the ventilation capacity. There is a positive correlation between the gas emission and the mining speed, and the gas emission varies with the change in mining speed.

Because the ventilation capacity of the working face is certain and the upper limit of gas concentration in the return air roadway is specified, it is necessary to coordinate the relationship between the mining speed and the gas emission. During the mining period of the working face, the volume of gas emitted from the coal seam and the volume of gas emitted from the adjacent seam should be within the range of the maximum amount of gas emitted from the working face. The volume of gas emitted from the coal seam includes the volume of gas emitted from the coal seam and adjacent seam when the working face is advancing at a certain speed. Therefore, the relationship between the mining speed and the volume of gas emitted from the wind is established:

$$q_{fp} t_h \leq \rho H L q_{fp} t_h (X_{ob} - X_{gcb}) + Q_{by} - x_{gb}$$

where $t_h$ is the mining time, $s$; $q_{fp}$ is the volume of gas discharged by the wind in the working face, $m^3/s$; $q_{by}$ is the total volume of gas discharged during mining, $m^3$; $X_{ob}$ is the initial gas content of the coal seam, $m^3/t$; $X_{gcb}$ is the residual gas content of this coal seam, $m^3/t$; $Q_{by}$ is the volume of gas emitted from adjacent layers, $m^3$; and $x_{gb}$ is the gas drainage volume in the mining process, $m^3$. 

Figure 6. Changes in the return air gas concentration and coal output during the mining process of the No. 22201 working face.

Figure 7. Change relationship between the gas election and coal output of the No. 22201 working face during the mining process.
Analyzing the gas drainage data of the 22201 working face, the relationship among the gas emission, drainage, and wind displacement in the working face is used to explain the influence of drainage on mining, as shown in Figures 6 and 7.

The air volume of the working face is 4000 m³/min. The gas volume of the wind discharged increases with increasing daily output, and it decreases with increasing drainage volume. In the early stage of mining, the volume of depressurized gas emission is small, and the output is extremely unstable from 400 t/d to 3200 t/d, with a maximum of 4000 t/d. The gas volume discharged by wind also fluctuates drastically with the change in the output by 9.2–23.39 m³/min, and the gas concentration is 0.23–0.58%. After the working face is advanced to 50 m, the production tends to be stable at 3200 t/d, the gas quantity discharged by the air is also stable between 15–20 m³/min, and the gas concentration in the return air is stable at 0.4–0.55%. After advancing to 230 m, the output increases to 3600 t/d. With the increase in pressure relief gas drainage, the air distribution volume decreases from 3300–4000 m³/min to 2100–2674 m³/min.

It can be seen from the calculation formulas of gas emission and mining speed and the production curve statistics that with an increase in the daily output, the gas emission increases, and with a decrease in the daily output, the gas emission decreases, which indicates a positive correlation. Moreover, from the field data statistics, it was also found that the gas concentration in the return air roadway is also positively correlated with the gas emission. If the gas emission is too large, the gas concentration in the return air will exceed the limit, and the mining must be stopped for rectification.

The gas emission is solved by the drainage and wind drainage. According to the principle of “all pumping should be done, and mining should be guaranteed by pumping”, the gas emission is mainly treated by drainage. As the drainage volume increases, the gas discharged by the wind will naturally decrease, which also reduces the gas concentration in the return air flow and ensures the safety of the mining process. The “Coal Mine Safety Regulations” stipulates that the gas concentration in the return air flow of the working face cannot exceed 1%, and each working face also determines the upper limit of the concentration according to the actual situation, such as 0.8% in the 22201 working face. Only by controlling the volume of the gas emission can the gas concentration be controlled to ensure the safety of the mining process. The daily output of the working face should be determined according to the principles of “determining production by wind” and “pumping should be exhausted, and pumping should ensure mining”.

3. RESULTS AND DISCUSSION

3.1. Mutual Feeding Relationship between Mining and Extraction. Through experimental research, the influence of coal mining on gas migration is summarized. The mined-out area was formed after the No. 2 upper protective layer was mined at the 22201 working face of the Shaqu Mine, and disturbances occurred during the mining process, which caused the stress states of the underlying coal and rock mass to change. After losing the load of the overlying rock, the coal and rock mass on the floor of the goaf expanded and deformed upward, and the protected layers No. 3 + No. 4 and No. 5 decompressed. During the mining process, fissures began to appear at the position of the opening and in front of the working face and slowly extended to the floor. The goaf range of the working face continued to expand with the advance-
ment, and the fissure expansion gradually became active and tended to be stable when approaching the stoppage line. During mining, the overlying strata caved and contacted the floor, the floor was compacted, and the stress returned to the initial value, which reduced the permeability of the No. 3 + No. 4 composite layer, and the stress decrease—increase—decrease law appeared. With advancement, the influence range of this law gradually expands. The mining disturbance of the working face was the key factor affecting gas flow in coal. The pressure relief caused by the mining of the protective layer increased the permeability of the overlying rock.

Gas migration will also affect coal mining. The actual project shows that when the advancing speed of the working face increases, there will be more gas emission in the coal seam, which will lead to the suspension, rectification, and restriction of the mining progress. If the advancing speed is too slow, the volume of the gas emission will be small, but the slow mining speed will also reduce the production efficiency. If the gas extraction time is too long, the extraction progress will also be slowed. Ultimately, it will affect the economic benefits of the mine. The periodic changes in the stress field, fracture field and gas flow field of coal and rock masses caused by coal mining determine the method and effect of the gas drainage. The timeliness of gas extraction determines the speed and safety of coal mining.

The gas drainage system runs through the whole process of coal mining. Coal mining causes the overlying rock to move and break, the stress field of the surrounding rock changes, and the movement of the rock layer causes the formation, expansion, and closure of cracks. The gas in the coal seam and adjacent layers is desorbed, migrated, and gathered under the action of mining. The mining process changes the environment of the stope and determines the method and mode of the gas drainage. At the same time, the stress field formed by coal mining and the fissure field formed in the coal and rock are the preconditions for the formation of the gas flow field in the reservoir. Using the fissure channel formed by the mining pressure relief for gas extraction, while obtaining resources, the gas emission intensity, coal seam gas content, and coal seam gas pressure of the working face are reduced, which can prevent disasters such as coal and gas outbursts, improve coal mining efficiency, and increase coal production capacity.

In the actual production process of mines, there is always spontaneous and irregular independent movement between the two systems. Coal mining and gas extraction are both independent and mutually restricted, as shown in Figure 8.

In terms of coal mining, the “Coal Mine Safety Regulations” stipulates that the daily output of the mine, the ventilation capacity of the mine, and the required ventilation volume must be re-determined every year before the mine arranges the mining and excavation construction operation plan. Its daily output is determined by the wind. One of the primary problems in determining production by wind is determining the coal output and mining speed of the working face according to gas problems in the mining process.

In terms of gas drainage, the “Interim Provisions on Coal Mine Gas Drainage Standards” clearly points out that the coal seam that should be drained must first be used to drain gas and then carry out mining work. It is required that the extraction effect must meet the requirements of the gas pre-extraction standard before the coal seam mining work can be carried out. Gas extraction in coal mines should adhere to the principle of “should be pumped as much as possible, and various drainage measures should be combined to achieve the balance of pumping, excavation, and mining”. The gas extraction rate index is determined according to the daily output and emission of the working face. For outburst coal seams, the gas content of the coal seam within the control range must be reduced to below the gas content of the coal seam initial outburst depth, or the gas pressure must be reduced to below the gas pressure of the coal seam initial outburst depth before mining operation.

With the continuous practice of coal and gas co-mining technology, engineers and technicians continue to use mining processes to cause rock formations to move as much as possible to improve coal recovery and gas extraction rates and maximize the exploitation of the two resources. For coexisting coal and gas resources, the issues of the reasonable and optimal amounts of resources to recover under the existing technical conditions and the evaluation of the co-mining of coal and gas still need further research. Therefore, how to optimize the scientific production capacity of coal production and gas extraction subsystems under the coal and gas co-mining system has become an important issue for achieving safe, efficient, environmentally friendly mining and scientific, efficient, and clean utilization of coal and gas.

3.2. Space-Time Synergy Relationship of Coal and Gas Co-mining. Collaboration refers to the process or ability of coordinating two or more different resources or individuals to achieve a certain goal in a coordinated manner. In 1971, German theoretical physics professor Hermann first proposed a relatively unified idea of system synergetics when studying laser theory. Among them, there is a disordered or ordered state between the society where human beings live and all kinds of things existing in the outside nature. Under certain specific conditions, there is a dynamic mutual transformation relationship between disorder and order. Disorder is the original chaotic state, while order is the cooperative state. Synergy refers to the coherent ability of elements to elements, which shows the nature of coordination and cooperation in the overall development and operation process.

For coal and gas co-mining, the mining stress field is produced by a reasonable coal mining method so that the coal and rock mass can be fractured, which is conducive to gas desorption and flow and forms a gas flow channel and rich area. Scientific and targeted gas extraction methods are used to efficiently extract gas to achieve the purpose of fully extracting gas and realizing safe and efficient coal mining. The coal mining subsystem and gas drainage subsystem always have automatic, irregular, independent, and disorderly motion with each other, but at the same time, the two subsystems are interrelated and restricted. It may also be influenced by other subsystems. Each subsystem is in constant dynamic motion in a cooperative motion mode formed by interrelation. The co-mining mechanism of coal and gas refers to the macroscopic and orderly structure produced by the synergy between the coal mining and gas extraction subsystems. The cooperation among subsystems determines the orderly structure of the system. By coordinating the coal mining system and gas extraction system, the sequence or cross influence of coal mining and gas pre-pumping, pumping and mining during mining, and goaf pumping after mining can be linked with order in time. For both coal and gas resources, the mining methods, costs, and prices are different. What kind of extraction method is used to extract gas, what should be the
reasonable value of gas drainage volume, and what should be the reasonable value of coal mining volume are all questions that need to be determined by scientific calculation methods.

As shown in Figure 9, there is a disordered working mode between the two subsystems of coal mining and gas drainage in the initial stage, but through the identification and analysis of the control parameters of the co-mining, an optimization model is established to optimize the co-mining parameters between the two subsystems. The two subsystems entered an orderly and advanced stage of cooperation and optimization.

The total economic benefits, coal recovery rate, and gas extraction rate are taken as the objective functions of coal and gas co-mining. By optimizing the volume of coal mining and gas extraction, the maximum recovery rate is achieved, while the overall benefit of the two resources is maximized.

Because the price of coal is higher than that of gas, with the advancement of mining, coal production increases and gas production decreases and the corresponding gas control cost increases, but the benefits generated by the increase in coal production in the early stage are far greater than the gas control cost, and the economic benefits continue to increase. When the coal output increases to a certain value, the cost of gas control is too high, which will lead to a decline in economic benefits. This is shown in Figure 10. When the outputs and times of coal mining and gas drainage reach the “balance point”, the resource recovery rate and benefit are the best. This balance point is the optimal co-mining relationship between coal mining and gas drainage.

The co-mining of coal and gas involves an intricate relationship between coal mining and gas extraction. For example, coal mining and gas extraction work together in a certain way to influence co-mining, including the interactions and effects of macrovariables, such as the relationship between the recovery rate and the gas emission, the relationship between the mining volume and the extraction volume, and “determining production by wind”. There are many factors affecting coal mining and gas extraction, and it is necessary to gradually clarify the connection between coal mining and gas extraction and build a theoretical solution model.

According to the relevant regulations and requirements formulated by state, industry and enterprises, through the optimization of the variables of coal recovery, gas predrainage, gas extraction during mining, postmining gas extraction, wind exhaust gas volume, predrainage time, and daily coal production, the constraint conditions of coal and gas co-mining are established. Therefore, these variables are regarded as the control variables of coal and gas co-mining. Taking the resource recovery rate and economic benefits as the common mining goals, the effective mining of coal and gas is realized. Under the premise of ensuring safe co-mining, from the perspective of the enterprise, the cost should be as low as possible to ensure the long-term operation of the coal enterprise and maintain a good environment for the coal industry.

By establishing a constrained nonlinear multivariable collaborative optimization model of coal and gas co-mining, compiling a co-mining optimization solution program, and substituting the basic parameters of the coal seam and gas in the working face, the optimization variables of the coal and gas co-mining working face are calculated. Furthermore, the optimization of the recovery rates of coal and gas resources and their economic benefits are realized. According to the optimized extraction speed or gas extraction volume of different production stages, spatiotemporal configuration conversion is performed based on the production operation process.

The coal and gas co-mining optimization model takes the coal recovery rate, gas recovery rate and economic benefit maximization as the objective function, which considers mining cost, sales price, safety factor, and macropolicy and other factors, and the objective function is
\[ P_{\text{max}} = (P_c - T_c + S_c)x_c - (C_c + C_g) + \sum_{i=1}^{n} (P_{g_i} - T_{g_i} + S_{g_i})x_{g_i} \]  
\[ n_{\text{max}} = \frac{x_c}{M} \]  
\[ n_{\text{gmax}} = \frac{x_g}{Q} \]

where \( P_{\text{max}} \) is the maximum profit obtained from the co-mining of coal and gas, yuan; \( P_c \) is the coal price, yuan/t; \( P_{g_i} \) is the gas price, yuan/m\(^3\); \( C_c \) is the coal production cost, yuan/t; \( C_g \) is the gas extraction cost, yuan/m\(^3\); \( T_c \) is the coal mining tax rate, yuan/t; \( T_{g_i} \) is the gas extraction tax rate, yuan/m\(^3\); \( S_c \) is the coal mining subsidy, yuan/m\(^3\); \( S_{g_i} \) is the gas extraction subsidy, yuan/m\(^3\); \( M \) is the total coal resources, t; \( Q \) is the total volume of gas resources, m\(^3\); \( n_{\text{max}} \) and \( n_{g_{\text{max}}} \) are the maximum resource recovery rates of coal and gas; \( x_c \) is the coal mining volume, t; \( x_{g_i} \) is the gas extraction volume, m\(^3\); \( x_{g_{\text{g}}}, x_{g_{\text{gb}}} \) are the pre-extracted gas volume of the working face before mining, m\(^3\); \( x_{g_{\text{gb}}} \) is the total gas extraction while mining at the working face, m\(^3\); and \( x_{g_{\text{g}}} \) is the total volume of gas extraction.

The coal mining constraint conditions are

\[
\begin{align*}
0 & \leq x_c \leq M \\
q_{\text{hp}} & \leq \rho H L q_{\text{hp}} q_{\text{hy}} + Q_{\text{hp}} - (x_{g_2} + x_{g_3}) \\
A & \leq v_q S_{\min} C (24 \times 60 \times 60) / K q_t \\
v_h & \leq v_q D n_{\text{at}} / L_q t \\
x_c / M & \geq n_t
\end{align*}
\]

The gas extraction constraint conditions are

\[
\begin{align*}
0 & \leq x_g \leq Q \\
x_g & \geq \eta_t (x_c + Q_{\text{hp}}) \\
Q_{\text{hp}} & \leq \eta_t S_{\min} C T / K \\
x_g & \geq Q_y - X_{\text{gcb}} \\
g & = g(q_{\text{hp}}, x_g, X_{\text{gb}}, q_{\text{hp}}, t) \\
q_{\text{hp}} & \leq (X_{\text{gb}} - X_{\text{gcb}}) \rho H L q_{\text{hp}} \]
\]

The optimization variables are \( x_{\text{c}}, x_{\text{g}}, x_{\text{g}2}, x_{\text{g}3}, Q_{\text{hp}} \), \( t, A \), and \( t_{\text{chc}} \), where \( Q_{\text{hp}} \) is the total amount of gas exhausted of the working face, m\(^3\); \( t_{\text{chc}} \) is the mining time of the goaf; \( s; t_f \) is the gas pre-extraction time of the working face, s; \( A \) is the average daily output, t/s; \( v_h \) is the recovery speed, m/s; \( q_{\text{hp}} \) is the gas discharge volume of the working face, m\(^3\)/s; \( \rho \) is the coal density, kg/m\(^3\); \( L_q \) is the inclination length of the working face, m; \( H \) is the mining height, m; \( q_{\text{gp}} \) is the absolute gas emission volume of the coal seam, m\(^3\)/s; \( Q_{\text{gb}} \) is the total gas emission of the adjacent layers, m\(^3\)/s; \( S_{\min} \) is the minimum roadway section through which the wind flow passes, m\(^2\); \( v_h \) is the maximum wind speed allowed in the roadway, m/s; \( C \) is the gas volume fraction in the wind flow allowed by the “Coal Mine Safety Regulations”, %. \( Q_{\text{hp}} \) is the average relative gas emission volume of the mine (mining area), m\(^3\)/t; \( K \) is the unbalanced coefficient of gas emission in the mine or mining area (working face); \( v_q \) is the traction speed of the coal cutter, m/s; \( \eta_t \) is the working efficiency of the coal cutter, %; \( t \) is the coal cutting time, d; \( D \) is the cutting depth, m/knife; \( n_t \) is the extraction rate determined according to the actual absolute gas emission; \( X_{\text{gcb}} \) is the possible residual amount of coal seam gas, m\(^3\)/t; \( Q_t \) is the total ventilation of the working face, m\(^3\)/t; \( T \) is the total ventilation time, s, \( T = t_f + t_b \); \( Q \) is the total gas emission from the working face, including the coal seam and adjacent layers, m\(^3\); \( X_{\text{gb}} \) is the original gas content of the mining layer, m\(^3\)/t; and \( x_{g_{\text{g}}} \) is the upper and lower adjacent layers.

By solving this optimization model, it was found that the optimal value of the recovery of the working face is 20.6 \( \times \) 10\(^5\) t, the optimal value of the total gas prepping is 87.7 \( \times \) 10\(^5\) m\(^3\), the optimal value of the total extraction volume in the recovery is 209.85 \( \times \) 10\(^5\) m\(^3\), the total extraction volume in the goaf area is 21.3 \( \times \) 10\(^5\) m\(^3\), the total amount of wind exhaust gas is 131.30 \( \times \) 10\(^5\) m\(^3\), the daily production is 2500.40 t/d (actual average 2787 t/d), and the prepumping time is 240 d. According to the on-site co-mining scheme, the recovery rate is 96%, the extraction rate is 65%, and the profit is 650 million yuan. After optimization, the coal recovery rate is 96%, the extraction rate is 66.7%, the profit is 756 million yuan, the profit is increased by 16.3%, and the gas extraction rate is increased by 2.6%. These results verify that the model is effective. According to the optimization solution results, the mining volume does not need to be adjusted, the prepumping volume and the pumping volume in the goaf should be reduced, and the amount of mining while pumping should be increased, which can not only ensure safety before mining but also improve the profit of coal and gas co-mining.

For outburst coal seams, the gas pressure must be reduced to 0.74. Combined with the optimized predrainage amount of 87.7 \( \times \) 10\(^5\) m\(^3\) and the predrainage time of 240 days, the predrainage borehole spacing is simulated and analyzed, as shown in Figures 11, 12, and 13. In Figure 9, it can be seen that when the drill hole spacing is 6 m, the gas pressure drops to 0.68 MPa when pumping for 240 days, which is much lower than 0.74 MPa, which will delay the recovery operation and lead to waste due to the overdensity of the drill holes; when
the drill hole spacing is 8 m for 240 days of pumping, the gas pressure is 0.78 MPa, which necessitates an increase in the pumping time; when the drill hole spacing is 7 m for 240 days of pumping, the gas pressure drops to 0.74 MPa, which reaches an optimal combination of pressure and time, which means that 7 m is the most reasonable drill hole spacing for the 24207 working face of the Shaqu mine.

4. CONCLUSION

(1) The coal and gas co-mining experiments show that the stress redistribution caused by mining affects the permeability and thus the coal and gas co-mining. The unloading coefficient decreases to 0.98 during mining, the corresponding relative change coefficient of permeability increases to 2.5, and the permeability change is more sensitive than the stress change. The spatial and temporal changes in coal mining lead to spatial and temporal changes in stress, which affect the spatial and temporal changes in permeability, and the spatial and temporal changes in stress and permeability have a corresponding relationship. The stress shows a decreasing—increasing—decreasing change law during the working face advancement, and the corresponding permeability shows an increasing—decreasing—increasing change law.

(2) The output of the 22201 working face is 400–3200 t/d in the initial stage of mining, and the gas discharge volume is 9.2–23.39 m³/min. The amount of gas exhausted by the wind is closely related to the daily output. After advancing to 230 m, the pressure relief range increases, the output increases to 3600 t/d, the extraction volume increases, and the air exhaust gas volume decreases. In the early stage of mining, the pressure relief range is small, and the control variables are the recovery volume and the air exhaust gas volume. In the middle of the recovery, the gas extraction volume increases, and the control variables are the recovery volume, the air discharge volume, and the extraction volume. The mining change in the coal and rock mass determines the method and effect of the gas drainage, and the timeliness of the gas drainage determines the speed and safety of coal mining.

(3) The coal mining constraints and gas drainage constraints are established considering the effects of the control factors. Taking the control variables that affect the co-mining as the optimization variables and the maximum economic benefit and resource recovery of the co-mining system as the objective function, a nonlinear optimization model is established for coal and gas co-mining, and the scientific production and gas drainage speed of the working face at different advancement stages are determined.

(4) According to the optimization results, the parameters of coal mining and gas drainage can be designed, and a method for determining the optimal advance speed and optimal gas drainage volume of the working face is formed. Through this optimization model, the optimization variables of the 24207 co-mining working face in the Shaqu Mine are calculated. After optimization, the profit is increased by 16.3%, and the gas extraction rate is increased by 2.6%. The drilling spacing is optimized according to the optimization results, and the simulation results show that 7 m is the optimal drilling spacing for the working face.

AUTHOR INFORMATION

Corresponding Author
Bing Qin — School of Mechanics and Engineering, Liaoning Technical University, Fuxin, Liaoning 123000, China; orcid.org/0000-0003-1701-0291; Phone: +86-137-9508-4408; Email: qinbing20071111@163.com

Authors
Zhanshan Shi — School of Mechanics and Engineering, School of Mining, Liaoning Technical University, Fuxin, Liaoning 123000, China
Jianfeng Hao — School of Mechanics and Engineering, School of Mining, Liaoning Technical University, Fuxin, Liaoning 123000, China; orcid.org/0000-0001-8726-0646
Donglin Ye — School of Mechanics and Engineering, School of Mining, Liaoning Technical University, Fuxin, Liaoning 123000, China
Bing Liang — School of Mechanics and Engineering, Liaoning Technical University, Fuxin, Liaoning 123000, China
Weiji Sun — School of Mechanics and Engineering, Liaoning Technical University, Fuxin, Liaoning 123000, China

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.2c00034

Notes
The authors declare no competing financial interest.
ACKNOWLEDGMENTS

This research was funded by the National Natural Science Foundation of China (52004118 and 51874166); Liaoning Technical University (LNTU20TD-11); and the Department of Education of Liaoning Province (LJ2020QNL009).

REFERENCES

(1) Yan, B. Y.; Cao, L. Gas Drainage Methods and Developing Direction of gob. Proceedings of The 8th Academic Conference of Geology Resource Management and Sustainable Development; Hubei Zhongke Geology and Environment Technology Institute, Beijing, China, December 19, 2020; Vol. 8.

(2) Li, X. L.; Cao, Z. Y.; Xu, Y. L. Characteristics and trends of coal mine safety development. Energy Sources, Part A 2020, 1–14.

(3) Brodny, J.; Tutak, M.; Michalak, M. A data warehouse as an indispensable tool to determine the effectiveness of the use of the longwall shearer. International Conference: Beyond Databases, Architectures and Structures. Springer, Cham 2017, 27, 453–465.

(4) Black, D. J. Review of coal and gas outburst in Australian underground coal mines. Min. Sci. Technol. 2019, 29 (29), 815–824.

(5) Beaman, B. B.; Crosdale, P. J. Instantaneous outbursts in underground coal mines: An overview and association with coal type. Int. J. Coal Geol. 1998, 35, 27–55.

(6) Qian, M. G.; Xiao, X.; Xu, J. L. Greening in ing of Coal Resources Harm on izing With Environment. J. China. Coal. Soc. 2007, 32, 1–7.

(7) Yuan, L.; Sheng. thinking of simultaneous exploitation of coal and gas in deep mining. J. China. Coal. Soc. 2016, 41, 1–6.

(8) He, X.; Yang, K.; Han, P.; Liu, W.; Zhang, Z.; Wu, H. Permeability Enhancement and Gas Drainage Effect in Deep High Gassy Coal Seams via Long-Distance Pressure Relief Mining: A Case Study. Adv. Civ. Eng. Mater. 2021, 2021, 1.

(9) Yi, M. H.; Wang, L.; Liu, Q. Q.; Hao, C. M.; Wang, Z. Y.; Chu, P. Characteristics of Seepage and Diffusion in Gas Drainage and Its Application for Enhancing the gas utilization rate. Transp. Porous Media. 2021, 137, 417–431.

(10) Chen, Y. X.; Chu, T. X.; Chen, X. X.; Chen, P.; Si, J. H.; Peng, R. Numerical simulation study of influencing factors for 3D coal seam gas drainage efficiency. Arabian J. Geosci. 2021, 14, 1–11.

(11) Hao, J. F.; Liang, B.; Sun, W. J. Experimental Study on the Thermal Effect during Gas Adsorption and Desorption on the Coal Surface. Adv. Mater. Res. 2021, 6, 1603–1611.

(12) Liu, P.; Fan, J. Y.; Jiang, D. Y.; Li, J. Evaluation of underground coal gas drainage performance: Mine site measurements and parametric sensitivity analysis. Process Saf. Environ. Prot. 2021, 148, 711–723.

(13) Zhang, P. Study on Gas Drainage Technology of High-level Borehole in Fully Mechanized Caving Face. IOP Conf. Ser.: Earth Environ. Sci. 2020, 558, 022079.

(14) Huijun, D.; Shijun, H.; Yongzhe, Z. Differential Gas Drainage Technology for Upper Corner of Working Face by High Position Directional Long Borehole. IOP Conf. Ser.: Earth Environ. Sci. 2021, 687, 012180.

(15) Liu, G. N.; Ye, D. Y.; Yu, B. M.; Gao, F.; Chen, P. J. A study on gas drainage considering coupling process of fracture-pore microstructure and coal deformation. Fractals. 2021, 29, 2150065.

(16) Sun, B. X. Gas Drainage Technology in Fully Mechanized Caving Face with Horizontal Sublevel Mining in Steep and Extra-Thick Coal Seam. Open J. Geol. 2020, 10, 957–970.

(17) Yang, L. P. Research on Complete Set of Gas Drainage Technology for Coal Mine Long Bedding Drilling. J. Appl. Sci. Eng. Innovation. 2020, 7.

(18) Zhang, R.; Cheng, Y. P.; Yuan, L. Study on the stress relief and permeability increase in a special low-permeability thick coal seam to stimulate gas drainage. Energy Sources, Part A 2020, 42, 1001–1013.

(19) Qian, Z. L. Research on Multi-directional Gas Drainage Technology in Goaf of Working Face. IOP Conf. Ser.: Earth Environ. Sci. 2020, 526, 012167.

(20) Yang, L. P. Research on Reasonable Hole Arrangement Parameters of Ground Drilling Gas Extraction Technology. J. Appl. Sci. Eng. Innovation. 2020, 7.

(21) Ying, L. M.; Chen, J.; Du, C.; Pang, L. X.; Wen, Y. J. The research progress of coal and gas co-mining. Adv. Mater. Res. 2012, 524, 489–493.

(22) Li, X. L.; Chen, S. J.; Zhang, Q. M.; Gao, X.; Feng, F. Research on theory, simulation and measurement of stress behavior under regenerated roof condition. Geomech. Eng. 2021, 26, 49–61.

(23) Liu, J.; Yang, T.; Wang, L.; Chen, X. Research progress in coal and gas co-mining modes in China. Energy Sci. Eng. 2020, 8, 3365–3376.

(24) Ma, N. J.; Guo, X. F.; Zhao, X. D.; Li, J.; Yan, Z. X. Theoretical analysis and application about permeability-increasing radius of drilling for simultaneous exploitation of coal and gas. J. China. Coal. Soc. 2016, 41, 120–127.

(25) Wu, R. L.; Wang, Y. F.; Xu, D. L.; She, Z. L.; Meng, L. Effects of working face width on the scope of the “three zones” of gas pressure relief and migration. J. Min. Saf. Eng. 2017, 34, 192–198.

(26) Li, S. G.; Wei, Z. Y.; Lin, H. F.; Zhao, P. X.; Xiao, P.; Hao, Y. Research and development of 3D largescale physical simulation experimental system for coal and gas co-extraction and its application. J. China. Coal. Soc. 2019, 44, 236–245.

(27) Cheng, X. Mechanical Effect and Application of Mining Relief-pressure for Soft Rock Protective Layer Mining in Deep Strong Outburst Coal Seam; Anhui University Of Science & Technology, 2019.

(28) Li, J.; Jiao, Z.; Zhang, M.; Li, Y. Dynamic evolution characteristics and mechanism of surrounding rock fractures during the repeated mining of closed distance deep coal seam. Revista International DE Contamination Ambiental. 2019, 35, 165–176.

(29) NING, J. G.; Wang, J.; Tan, Y. L.; Xu, Q. Mechanical mechanism of overlying strata breaking and development of fractured zone during close-distance coal seam group mining. Int. J. Min. Sci. Technol. 2020, 30, 207–215.

(30) Yuan, X. P.; Liang, B.; Sun, W. J.; Zhang, X. P. Synergistic mechanism of-co-mining coal and gas in overburden strata fissure zone. J. China. Univ. Min. Technol. 2020, 49, 289–295.

(31) Yuan, B. Q. Study on the co-mining mode of coal and gas in protective layer of coal seam group. IOP Conference Series: Earth. Environ. Sci. 2020, 558, 022081.

(32) Zhang, N.; Xue, F.; Zhang, N. C.; Feng, X. W. Patterns and security technologies for co-extraction of coal and gas in deep mines without entry pillars. Int. J. Coal. Sci. Technol. 2015, 2, 66–75.

(33) Liu, L.; Cheng, Y. P.; Wang, H. F.; Wang, L.; Ma, X. Q. Principle and engineering application of pressure relief gas drainage in low permeability outburst coal seam. J. Min. Sci. Technol. 2009, 19, 342–345.

(34) Wang, L.; Lu, Z.; Chen, D. P.; Liu, Q. Q.; Chu, P.; Shu, L. Y.; Ullah, B.; Wen, Z. J. Safe strategy for coal and gas outburst prevention in deep-and-thick coal seams using a soft rock protective layer mining. Saf. Sci. 2020, 129, 104800.

(35) Liu, S. M.; Li, X. L.; Wang, D. K.; Zhang, D. M. Experimental study on temperature response of different ranks of coal to liquid nitrogen soaking. Nat. Resour. Res. 2021, 30, 1467–1480.

(36) Liang, B.; Qin, B.; Sun, W. J.; Wang, Y.; Sun, Y. N.; Phuc, K. Application of evaluation index system of coal and gas co-extraction and evaluation model. J. China. Coal. Soc. 2015, 40, 728–735.

(37) Hao, J. F. Research on Optimization of Simultaneous Exploitation of Coal and Gas Collaboratively of Single Seam; Liaoning Technical University, 2016.

(38) Qin, B.; Hao, J. F.; Liang, B.; Sun, W. J.; Qin, X. W.; Li, C. Z. Nonlinear constrained multivariable spatiotemporal collaborative optimization model for coal and gas co-mining. J. China. Coal. Soc. 2019, 44, 593–600.

(39) Liang, B.; Gai, D.; Sun, W. J.; Wang, W. H.; Yuan, X. P.; Ding, X. C.; Qin, B. Similar simulation experimental device for coal and gas CO mining. CN patent CN203053723, 2013.

(40) Cheng, Z. H.; Chen, L.; Zou, Q. L.; Pu, S. J.; Qi, Q. X.; Liang, C.; Fan, S. W.; Su, S. L.; Yan, D. H. Study on high-efficiency co-
mining technology system of coal and gas in contiguous seams: a case study of Shaqu Mining Area in Lüliang, Shanxi Province. Coal. Sci. Technol. 2021, 49, 122–137.

(41) Cheng, Z. H.; Pan, H.; Zou, Q. L.; Li, Z. H.; Chen, L.; Cao, J. L.; Zhang, K.; Cui, Y. G. Gas Flow Characteristics and Optimization of Gas Drainage Borehole Layout in Protective Coal Seam Mining: A Case Study from the Shaqu Coal Mine, Shanxi Province, China. Nat. Resour. Res. 2021, 30, 1481–1493.

(42) Lin, B. Q.; Zhang, J. G. Theory and technology of mine gas drainage, 2nd ed.; University Press: Xuzhou, 2007; pp 25–30.

(43) State Administration of work safet.; State Administration of Coal Mine Safety. Coal mine safety regulations; Coal Industry Press, 2016.

(44) State Administration of work safet.; National Development and Reform Commission.; State Administration of Coal Mine Safety. Interim Provisions on reaching the standard of gas drainage in coal mines; Coal Industry Press, 2012.

(45) Guo, H.; Yuan, L.; Shen, B. T.; Qu, Q. D.; Xue, J. H. Mining-induced strata stress changes, fractures and gas flow dynamics in multi-seam longwall mining. Int. J. Rock Mech. Min. Sci. 2012, 54, 129–139.

(46) Haken, H. Synergetics-An Introduction, 1st ed.; Springer Verlag: Berlin, 1977; pp 1–10.