Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Research and applications of gas distribution space form under the synergistic effect of injection and extraction in goaf of high gas and thick coal seam

Yibo Zhang
Xi'an University of Science and Technology
Shugang LI
Xi'an University of Science and Technology
Pengxiang Zhao
zhpxhs@sina.com
Xi'an University of Science and Technology
Risheng zhuo
Xi'an University of Science and Technology
Haifei Lin
Xi'an University of Science and Technology
Hongxing sun
Yankuang Xinjiang Mining
Jiajia liu
Henan Polytechnic University
Cuixia wang
Xi'an University of Science and Technology
Li Li
Xi'an University of Science and Technology
yu shi
Xi'an University of Science and Technology

Research Article

Keywords: High-gas giant coal seam, Nitrogen injection displacement, Negative pressure synergy, Gas concentration distribution, Response surface optimization

Posted Date: August 31st, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9285127/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Research and applications of gas distribution space form under the synergistic effect of injection and extraction in goaf of high gas and thick coal seam

Yibo ZHANG [1], Shugang LI [1,2], Pengxiang ZHAO [1,2,3 *], Risheng ZHUO[1,2 **], Haifei LIN [1,2] , Hongxing Sun [4], Jiajia LIU[5] Cuixia WANG [1], Li LI [1,2], Yu SHI [1,2]

[1] Department of Safety Science and Engineering College of Xi 'an University of Science and Technology, Xi'an Shaanxi, 710054, China.

[2] Western Engineering Research Center of Mine Gas Intelligent Drainage for Coal Industry,Xi'an Shaanxi, 710054, China.

[3] Key Laboratory of Green Mining of Coal Resources in Xinjiang Ministry of Education, Xinjiang Institute of Engineering, Urumqi, Xinjiang 83002, China.

[4] Yankuang Xinjiang Mining Co., Ltd. Sulfur ditch coal mine, Xinjiang 831100, China.

[5] School of Safety Science and Engineering, Henan Polytechnic University, Jiaozuo 454003, China.

*Corresponding author: Pengxiang Zhao, Risheng ZHUO

Tel.: +86-159-9166-3970, +86-181-9176-1425

E-mail address:

zhpxhs@sina.com (P. Zhao). zhuorisheng@163.com (R. Zhuo).

ABSTRACT

To address mine safety accidents triggered by gas accumulation in the goaf of high-gas giant coal seams, this study systematically investigated the gas migration laws and distribution characteristics under the combined action of nitrogen injection displacement and negative-pressure extraction. The

research was grounded in the theory of porous media and employed numerical simulation methods. Based on the actual working conditions of the site, the geometric model and boundary conditions of the goaf were constructed. By integrating the central composite design (CCD) and the response surface model, the synergistic effect of nitrogen injection flow rate (0.75–1.35 m/s) and extraction negative pressure (5–25 kPa) on the gas concentration distribution was quantitatively analyzed. The results indicated that with the increase of nitrogen injection flow rate, the diffusion penetration and displacement effect of nitrogen in goaf were enhanced, the displacement range was substantially expanded (the displacement efficiency was increased by 31.5%), and the methane was forced to float up to form a high concentration gas “dome” at the top, and notably lessening the concentration of gas in the working face. Combined with the optimization of negative pressure of extraction, the directional migration of gas was driven by pressure gradient, and the directional migration of nitrogen-gas mixed gas was driven to the extraction hole to break the local accumulation, and drive the high concentration gas to the upper part of the goaf. The synergistic effect of the two can achieve accurate regulation of parameters through dynamic matching equations. The response surface model validated that the nitrogen injection flow rate had a dominant influence on gas concentration. The engineering practiced demonstrates that the extraction efficiency of the injection-extraction synergistic process based on the closed-loop control mechanism was distinctly improved by 36%, with optimized parameters (1.20 m/s, 20 kPa), the extraction volume is stable at more than 50 m^3/min, which effectively mitigated the gas accumulation in the working area and ensured the production safety during the mining of the working face. The research findings offered an effective solution for the safe mining of high-gas giant coal seams and facilitated the iterative upgrading of gas disaster prevention and control technologies.

KEY WORDS:

High-gas giant coal seam, Nitrogen injection displacement, Negative pressure synergy, Gas concentration distribution, Response surface optimization

INTRODUCTION

The goaf is predominantly composed of collapsed and fragmented rocks, forming complex and irregular porous media. These porous media are the primary causes of coal mine disasters, including gas explosions and coal spontaneous combustion. Statistics shows that gas emissions from the goaf account for 30%–60% of the total mine gas emissions. Treating these gas is the core challenge in ensuring coal mine safety production. Owing to the accumulation of gas in the goaf[1][2] , mine disasters, such as gas explosion may occur in contact with the air in the working face[3]. With the increase of mining depth, coal seam occurrence conditions are complex[4-6], high gas mine goaf accidentsoccur frequently[7], and traditional physical detection methods are limited, numerical simulation has increasingly become the core approach for researching gas migration and extraction processes[8].

Gas accumulation in the goaf ranks among the core issues endangering coal mine safety. Efficient extraction and control of mine gas disasters have long been the focal points of research in coal mine safety production. In view of different geological conditions and mining methods, scholars have made a series of breakthroughs in the regulation of gas migration channels in goaf, location of enrichment areas, and coordinated extraction. During the layered mining of extra-thick coal seams, the migration of pressure-relieved gas from the lower part to the goaf substantially elevates the difficulty of gas control in the upper-layered working face. This often leads to gas overrun issues in the upper corner [9][10]revealed the dynamic evolution law of permeability in the lower part of extra-thick coal seams via experiments and COMSOL numerical simulation. They proposed a gas interception technology based on long boreholes, which effectively balances extraction efficiency and borehole damage risk, offering

technical support for precise gas control in extra-thick coal seams. Cheng et al.[11]combined numerical simulation with measured data to quantitatively appraise the linear relationship between propulsion speed and gas emission. The increase of the advancing speed will alleciate the height of the penetrating fracture of the overlying rock, but the layered fracture is less affected by the mining speed. Zhao et al. [12]revealed the law that the increase of advancing speed leads to the decrease of caving zone height and the decrease of fracture fractal dimension through physical similarity simulation and fractal dimension theory. It lays a theoretical foundation for the accurate identification and extraction design of gas enrichment area under different mining speed conditions. As a crucial geological parameter, the thickness of coal seam directly influences the structural characteristics of gas migration channels. Zhuo et al.[13] based on fractal dimension theory, revealed the variation trends of gas channel height and width under varying mining height conditions. This research established a theoretical foundation for determining the optimal horizons of high-level boreholes. Combined with the dual verification of physical simulation and theoretical model, Zhao et al.[14] clarified the quantitative influence of recovery rate on overburden fracture, and provided a new method for multi-scale characterization of fracture network by fractal dimension. Shu[15] through numerical simulation and field tests, discovered that a reasonable hole arrangement can noteworthily suppress gas enrichment in the lower goaf and prevent air leakage from interfering with extraction efficiency. Li et al.[16] integrated geophysical exploration with porous media seepage theory to uncover the synergistic migration laws of residual coal desorption gas and adjacent layer gas within the fracture zones of middle and low overlying strata in the goaf.

Numerical simulation technology provides vital theoretical support for revealing the law of gas migration in goaf, but the prevention and control of gas disasters in practical engineering still requires to rely on a diversified management technology system. In the methane control of composite goaf, Liu

et al.[17] exploited the complexity of multi-source emissions and air leakage channels and employed SF6 tracer technology to accurately identify the multi-path air leakage channels within the goaf. Subsequently, they constructed a multi-leakage coupling numerical model, thereby offering an optimization scheme for the dynamic balance of multi-source emissions in high gas mines. To address the issue of gas overrun in the goaf of multi-roadway U-shaped working face, Zhang et al.[18] proposed the buried pipe extraction technology of closed contact roadway. By comparing the gas distribution characteristics under different parameters through numerical simulation, the efficient inhibiting ability of buried pipe parameter optimization to local gas enrichment was verified. The heterogeneity of gas spatio-temporal distribution within the W-type ventilated goaf imposes more stringent requirements on precise extraction. Jia et al.[19] integrated numerical simulation and field measurement and revealed that the gas concentration in the goaf expeditiously increases within 0–75 m range along the strike and exhibited a symmetrical distribution along the dip direction. Wang et al.[20] conducted a Fluent simulation to compare the applicability of buried pipe extraction and high-level drilling technologies in high-gas goafs. Based on the results, they provided an optimization concept for the combination of multiple technologies under complex conditions. Regarding the multi-source gas collaborative extraction in the goaf, Qian[21] proposed a multi-directional combined technology involving low, medium, and high-level boreholes. This technology significantly enhanced the gas replacement efficiency in the goaf through borehole relay extraction. As a result, pronounced borehole extraction effect surpassed the expected target, effectively alleviating the gas pressure during the normal mining of the working face. Moreover, it provided an engineering paradigm for the expeditions response to abnormal gas overrun areas.

Leveraging the unique properties and straightforward operation of nitrogen gas, the nitrogen

injection inerting process and nitrogen replacement gas technology have been gradually applied in various fields. These include improving coal seam gas permeability and gas displacement[22], goaf gas replacement, as well as flame retardancy and explosion prevention[23]. Zhang et al.[24] focused on efficiency optimization of coalbed methane pressure measurement. By constructing a multi-component gas migration model for active nitrogen injection, combined with the numerical solver developed by OpenFOAM, the matching relationship between nitrogen injection pressure and original coal seam pressure was revealed. To address the limitations of traditional negative pressure extraction technology, Ji et al.[25] proposed a novel pulsed pressure nitrogen injection method for enhancing coalbed methane extraction. Through a comparison of CH_4 displacement experiments under uniform pressure and pulse pressure, they discovered that pulse injection can remarkably increase methane recovery while lowering nitrogen costs. Chen et al.[26] explored the coupling relationship between nitrogen injection position and negative pressure distribution in goaf by combining field monitoring with CFD simulation. Based on Newton interpolation polynomial, the quantitative model of optimal nitrogen injection point N(x) and negative pressure distance (y) was established, and the optimal nitrogen injection time corresponding to different negative pressure positions was verified. Based on the downhole nitrogen injection test, Gong et al.[27] systematically assessed the dynamic law of nitrogen-driven coalbed methane emission. Leveraging a back propagation neural network model, this study predicted the efficacy of nitrogen injection and unveiled the multi-scale dynamic mechanism of nitrogen replacement. These findings served as a theoretical cornerstone for developing intelligent nitrogen injection processes. Liu et al.[28] constructed a numerical model of nitrogen enhanced coalbed methane recovery (N_2-ECBM) utilized on COMSOL software, revealed the dynamic coupling relationship between gas injection pressure and permeability evolution, and clarified the equivalent stress effect induced by

nitrogen injection via concentration difference and pressure gradient. Wang et al.[29] conducted CH_4 flooding experiments in tectonic coal to compare the mechanisms of CO_2 and N_2 under different displacement modes, namely isobaric diffusion and high-pressure injection. These experiments provided an experimental basis for optimizing the mixed gas injection process. Shi et al.[30] established a synergistic enhanced recovery model for CO_2/N_2 mixed gas displacement and pressure relief drilling in deep low-permeability coal seams. They employed the response surface method to reveal the coupling effects of the pressure relief cavity diameter, gas injection pressure, and CO_2 concentration on recovery efficiency (REE). Furthermore, they proposed the "injection-production alternation-multistage optimization" technology to maximize the gas displacement efficiency of low-permeability coal seams by adjusting the gas injection strategy in stages. Wen et al.[31] comprehensively reviewed the research progress of gas injection enhanced coalbed methane extraction from micro, mesoscopic, and macro scales. It was proposed that intelligent gas injection technology and multi-scale coupling model should be developed in the future to overcome the bottleneck problem of gas migration in low-permeability coal seams.

Existing research has confirmed that nitrogen injection can improve gas extraction efficiency through concentration replacement effect, and inhibit coal spontaneous combustion by abating oxygen concentration. At present, nitrogen injection replacement gas technology in goaf has gradually become the focus of research[32]. However, in the case of high gas content in extremely thick coal seams, the goaf has a large spatial scale and complex gas occurrence patterns. The influence mechanism of the parameter matching in the nitrogen injection-extraction collaborative process remains unclear, the dynamic regulation law of nitrogen injection-extraction parameters on heterogeneous seepage field has not been established, which restricts the engineering application effectiveness of this collaborative

process. This study employed COMSOL numerical simulation to construct a nitrogen-gas migration model for heterogeneous goafs. It investigated the impacts of nitrogen injection flow rate and extraction negative pressure on the gas distribution within the goaf and proposed a collaborative optimization scheme. Determining appropriate nitrogen injection parameters and extraction negative pressure can enhance the efficiency of gas extraction in the goaf, as well as attenuate the incidence of coal mine accidents.

EXPERIMENTAL DESIGN MODEL

Geometric Model

A geometric model was constructed using COMSOL to simulate the typical structure of the goaf in extremely thick coal seams. The goaf measures 400 m in height, 300 m in width, and 130 m in length. The model incorporates the intake airway and the return airway. In addition, “1# drilling field” and “2# drilling field” are set up in the return airway, corresponding to nitrogen injection hole and extraction hole, respectively, as depicted in Figure 1. The spatial relationship between the layout and the goaf mirrors the requirements for safe mining in practical engineering projects. By means of geometric parametric design, the model can conduct a further analysis of the concentration distribution of nitrogen and gas in the process of nitrogen injection-extraction in goaf, and furnish technical guidance for the prevention and control of gas disasters in mined-out areas.

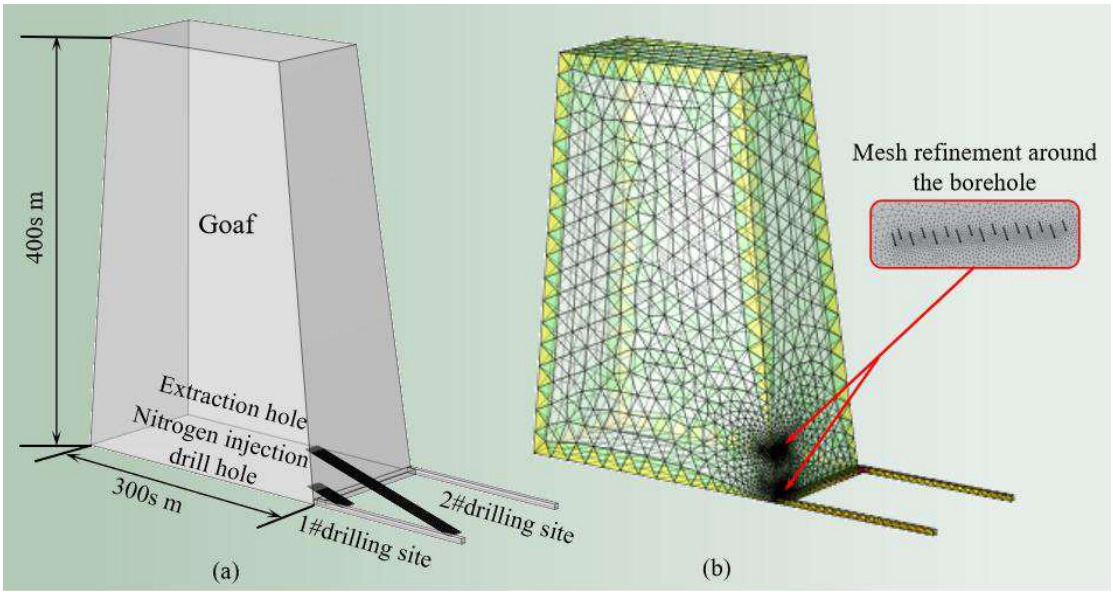


Figure 1. Three-dimensional model of injection-drainage synergy in goaf: (**a**) Geometric model; and (**b**) mesh subdivision.

Basic Assumptions of the Model

This experiment primarily focuses on simulating the distribution state of nitrogen-displaced gas in the goaf. Using the (9-15)08 working face of Liuhuanggou Coal Mine in Xinjiang as a prototype, owing to the complexity of the site, it cannot be directly solved by relying solely on the physical field and custom functions. Therefore, reasonable assumptions are also necessary. The following assumptions were made:

(1) The rock mass within the goaf is stable, and the interior exhibits a porous medium structure. The mixture of nitrogen and gas is considered an incompressible ideal gas, and the goaf is assumed to be filled with methane gas.

(2) In this numerical simulation, the effects of temperature and other factors on the simulation results are not considered.

(3) The gas migration under the combined action of injection and drainage is treated as a transient process. The sequential coupling method is employed to lessen computational complexity.

(4) The gas injection hole and the extraction hole are simplified as regular geometric boundaries.

The gas injection flow rate is assumed to be constant and evenly distributed along the borehole, and extraction negative pressure is considered to be in a steady-state condition. The peripheral boundary of the goaf is set as either an impermeable rock layer or a fixed pressure boundary, and the connected area between the surface and the roadway is treated as having zero gas flux.

Mathematical Parameters and Boundary Conditions of Goaf

As the working face is mined, the rock mass within the goaf is gradually squeezed and subjected to collisions due to the pressure of the overlying strata. This process leads to the fragmentation of the rock mass and the formation of gaps. Under the interaction between rock masses and continuous pressure, the goaf is finally filled with broken rock mass and its pores[33]. By integrating porous media theory with the complex realities of actual goaf working conditions, this research models the goaf as a heterogeneous porous medium system. This structure is composed of broken rock mass and a pore network. According to the theory of porous media, the characteristics of the goaf can be described by permeability (k) and porosity (ϕ)[34]. Gas and other gases flow and diffuse between broken rock mass and pores. In this study, three-dimensional simulation experiments were used and the following mathematical models were constructed:

First of all, the expression of the expansion coefficient of rock collapse is expressed by Eqs. (1) and (2):

$$K_P = K_{p,\min} + \left[K_{p,\max 1} + \varepsilon\left(K_{p,\max 2} - K_{p,\max 1}\right)e^{-a_2 d_2} - K_{p,\min}\right]e^{-a_1(d_1+b_1)\left(1-e^{-\varepsilon_0 a_0(d_0+b_0)}\right)} \quad (1)$$

$$\varepsilon = 1 - \frac{1}{K_p} \quad (2)$$

where: K_P is the bulking coefficient between rock blocks in caving zone of goaf; $K_{P,min}$ is the expansion coefficient between the crushed rock blocks after compaction, take 1.1; $K_{P,max1}$ is the distance between the point (x, y, z) and the working face, the distance between the point (x, y, z) and the surrounding

211 wall of the goaf, and the distance between the point (x, y, z) and the floor. Here b_0 is the control
212 parameter to adjust the depth of goaf, m; b_1 is the control parameter to adjust the direction of the
213 working face, m; The attenuation rate of a_2 pore distance from goaf roof, m^{-1} ; $\varepsilon_0$denotes the parameter
214 for adjusting the bluntness of the porosity distribution, and ε_1 is determined by the field conditions.

215 The expression of permeability in goaf Eg.(3) is as follows :

$$k = 1.605 \times 10^{-6}\varepsilon \quad (3)$$

216 The rock blocks in the goaf are affected by the stress of the surrounding rock, and the rock blocks
217 collide and squeeze with each other, so that the gap between the rock masses fills the holistic goaf.
218 Therefore, in the process of experimental simulation, the goaf is regarded as a porous medium, and the
219 process of nitrogen replacing gas in the goaf conforms to Darcy's law. In the fracture system of the
220 goaf, it is assumed that the free gas conforms to the Darcy's seepage movement, and the expression of
221 Darcy's law is as follows :

$$\frac{\delta}{\delta t}(\varepsilon_P \rho) + \nabla(\rho u) = Q_m \quad (4)$$

$$u = -\frac{k}{\mu}\nabla p \quad (5)$$

222 In the Egs.(4) and (5): ρ is gas density, unit kg/m^3; ε_P is porosity, unit 0–1 dimensionless
223 number ; u is the gas seepage velocity, m/s ; Q_m is the mass source ; k is permeability, $kg/(m^3 \cdot s)$; μ is
224 the gas dynamic viscosity coefficient, Pa·s; ∇p is the change of gas pressure, Pa.

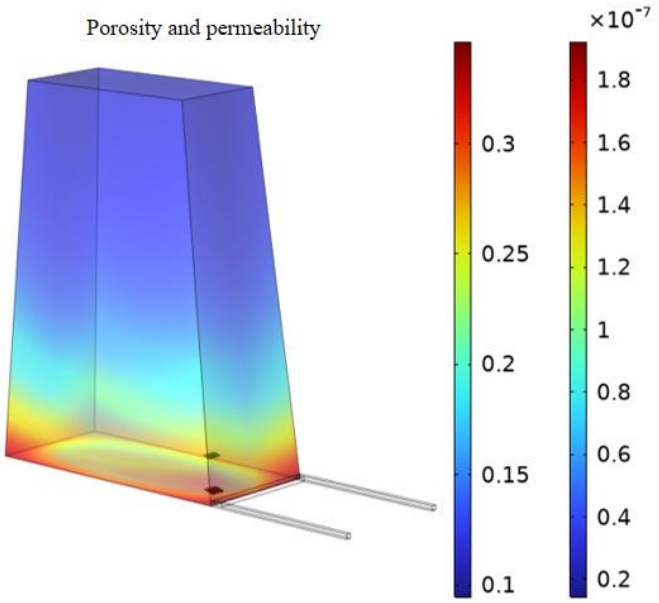


Figure. 2. Three-dimensional distribution map of porosity-permeability in goaf.

To solve the flow field, reasonable boundary conditions must be established. In this experiment, during the numerical simulation of nitrogen gas migration in the goaf of fully-mechanized caving, the boundary conditions were set to be as close to the actual situation as possible. The specific settings are as follows:

Inlet boundary: The No. 1 drilling field was designated as the velocity inlet for nitrogen injection. The nitrogen flow rate across the section was evenly distributed, with normal air inflow, and no other gas flow occurred inside the system.

Exit boundary: The No. 2 drilling field was set as the pressure outlet for gas extraction. Boundary conditions: A zero - velocity no - slip boundary condition was applied to the inner surfaces of both the nitrogen injection ports and gas extraction orifices. Under the model assumptions, gas movement in the goaf is subject to gravitational influence along the negative Z-axis. The domain exhibits no internal gas flow pathways other than at the defined inlet and outlet boundaries. The internal convection conformed to the Darcy's velocity field.

Analysis of Gas Concentration Distribution in Goaf Under Different Influencing Factors

Effect of Nitrogen Injection Flow Rate on Gas Concentration Distribution

A change in nitrogen injection velocity would induce a change in gas migration within the goaf. It is to understand the impact of varying nitrogen inlet velocities on gas distribution in the goaf. As boundary conditions, a constant gas emission value was specified for the goaf, while the extraction negative pressure was held at a fixed level. Under different nitrogen injection flow rates (0.75, 0.90, 1.05, 1.20, and 1.35), the spatial patterns of gas dissemination in the goaf were systematically characterized. Based on the nitrogen injection model in goaf, dynamic relationship between nitrogen injection velocity and gas concentration distribution was analyzed in depth.

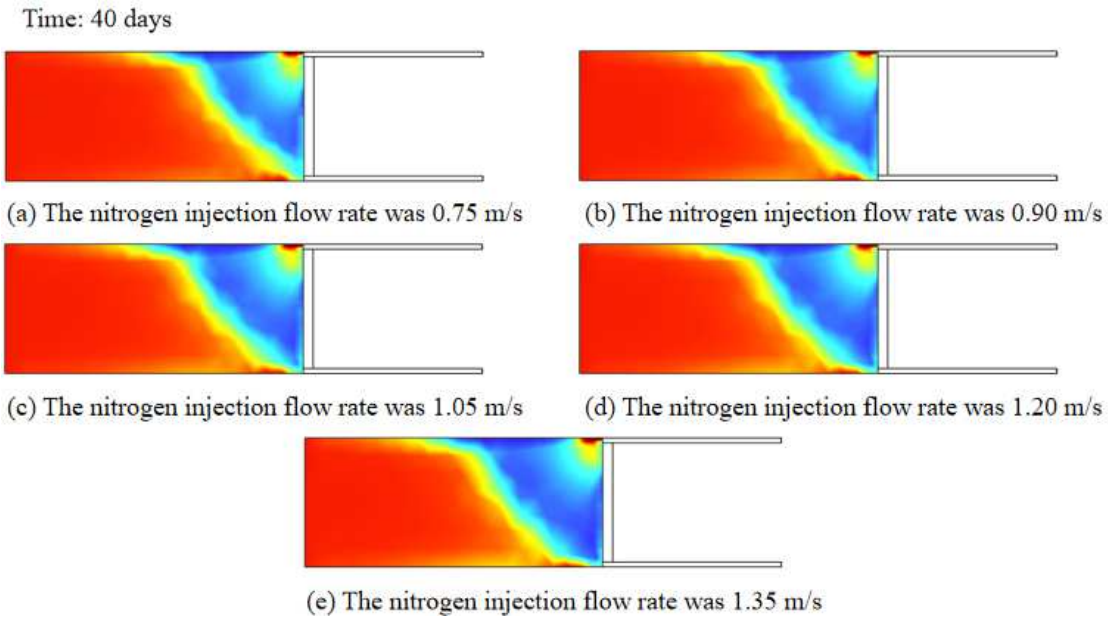


Figure 3. Gas distribution cloud diagram along the bottom surface of goaf under different nitrogen injection flow rates.

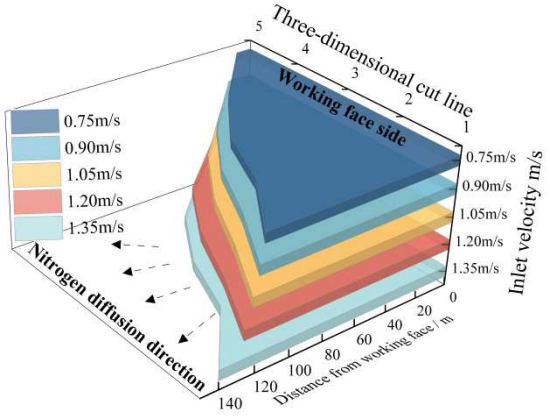
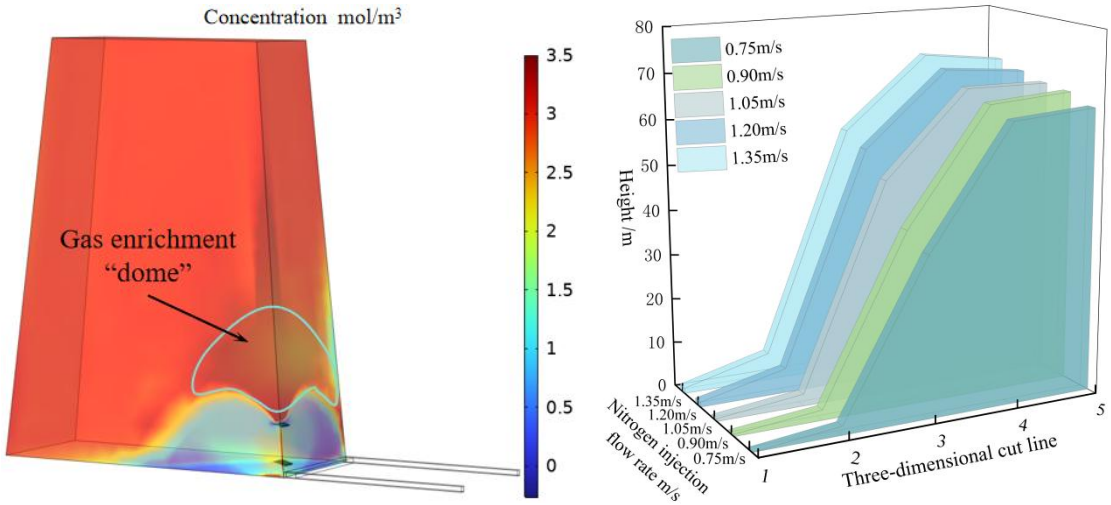


Figure 4. Bottom data map of survey line.

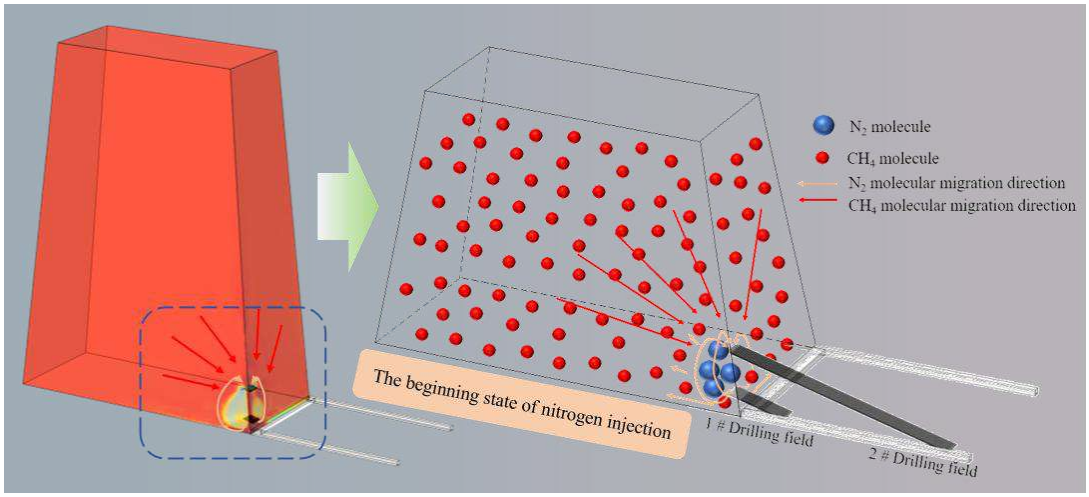
Figure 3 illustrates the distribution map of gas along the bottom in the process of nitrogen displacing gas along the bottom of the goaf. As depicted in Figure 3, because the density of nitrogen is higher than that of methane, it preferentially settles and diffuses along the bottom of the goaf during nitrogen injection, forming an “air cushion” and driving up the methane with lower density. In Figure 4, the displacement distance of nitrogen at section 1 increased from 117.8 to 140.2 m. This increase indicated that, as the inlet flow rate rose, the penetration of nitrogen into the deep part of the goaf was enhanced, and the displacement efficiency of the distal area was saliently improved. The total length of each cut-off line increased from 336 m at a flow rate of 0.75 m/s to 442 m of 1.35 m/s, and the displacement efficiency increased by 31.5%. With the increase of flow rate, the nitrogen displacement range was notably expanded, and the average gas concentration exhibited a downward trend.



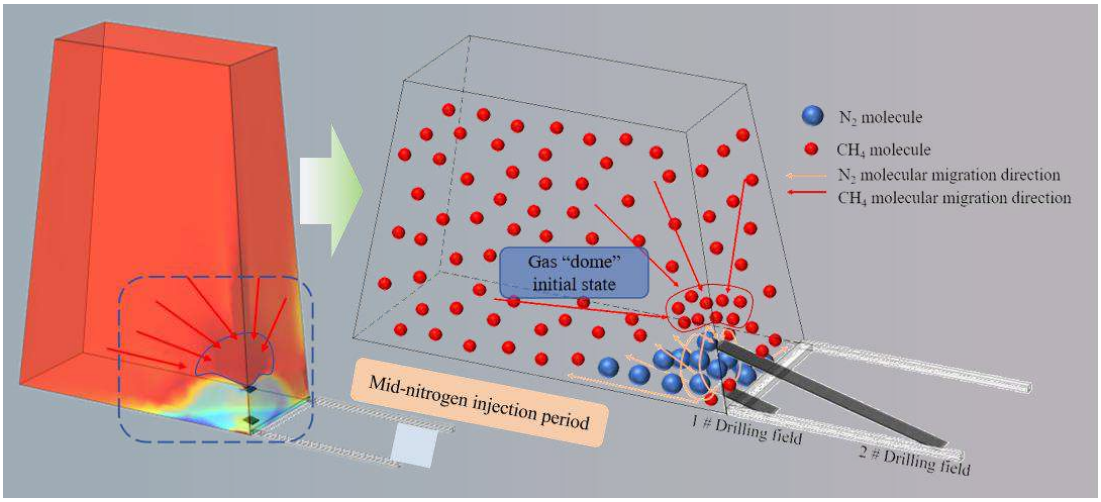
(a) (b)

Figure 5. The overall distribution of gas and gas height data in goaf after 40 days of nitrogen injection: (a) The overall distribution of goaf gas in the process of injection-drainage; and (b) Line height data map.

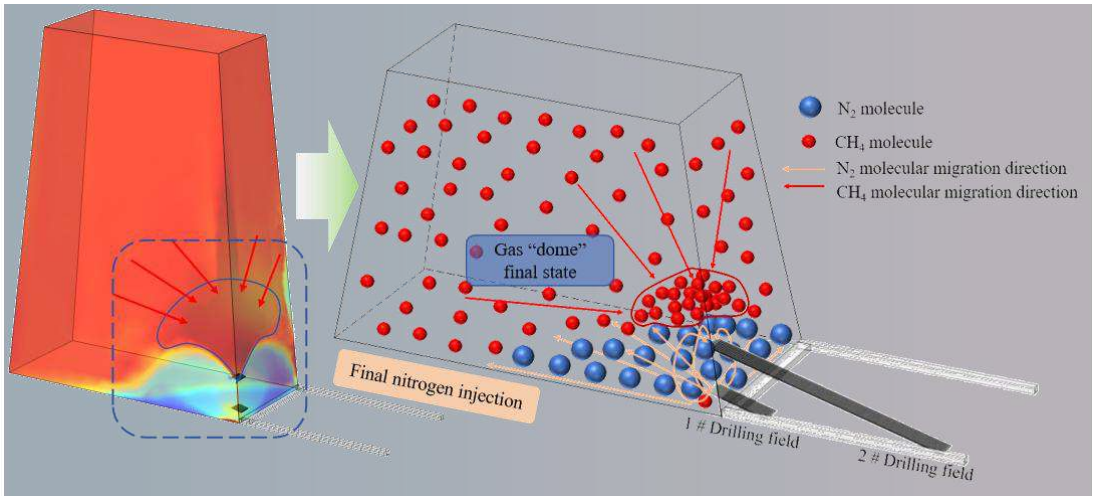
Figure 5 presents the height-development diagram of nitrogen displacing gas within the goaf during the nitrogen injection process. As illustrated in Figure 5 (a), in the process of continuous nitrogen injection, the gas was displaced by nitrogen because of its lower density, and accumulated in the upper part of the goaf to form a "dome" shape. As illustrated in Figure 5 (b), with the increase in flow rate, both the permeability of nitrogen and the gas-dilution ability within the goaf were enhanced. Consequently, influenced by nitrogen, the distribution height of the gas within the goaf demonstrated a progressive increase. At three deep cut-offs in the goaf, the height increased from 36.6 to 55 m at low flow rate compared with high flow rate (0.9 – 1.05 m/s). Nitrogen is easier to penetrate into the goaf and has a more prominent displacement effect on deep gas; Line 5 is close to the side of the working face, which is most substantially affected by nitrogen displacement, with the increase of flow rate, the height of gas "dome" increased from 62.9 to 68.2 m. The displacement efficiency of nitrogen to gas was higher at high flow rate, and the gas within the goaf demonstrated a progressive increase.



(a)



(b)



(c)

Figure 6. Gas distribution space diagram in the process of nitrogen injection: (**a**) the beginning stage of nitrogen injection; (**b**) mid-nitrogen injection period; and (**c**) final nitrogen injection.

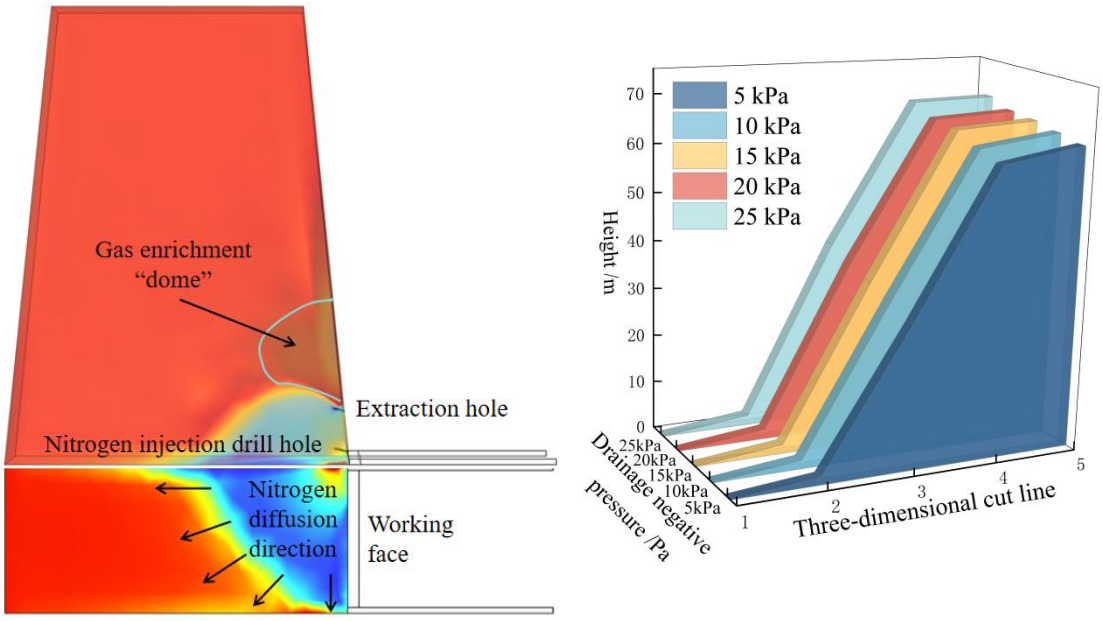
Figure 6 depicts a schematic diagram of the gas distribution space during nitrogen injection into the goaf. During the initial stage of nitrogen injection, the gas within the goaf existed in a natural diffusion state, exhibiting a high overall concentration. Low-density nitrogen diffused from the injection port into the goaf. Simultaneously, it squeezed and displaced the free gas, causing the gas to migrate towards the extraction hole. At this stage, the local gas concentration decreased due to the mixing of nitrogen and gas. However, since the extraction negative pressure has not yet exerted a substantial synergistic effect, neither has the gas enrichment area formed nor has the gas concentration at the working face been effectively diluted. With the continuous injection of nitrogen, it migrated towards the deeper regions of the goaf. In combination with the extraction negative pressure, it drove the gas to accumulate above the extraction hole, gradually forming a “dome”-shaped enrichment area; in the lower region of the nitrogen injection hole and the upper corner of the goaf, owing to the airflow disturbance and vortex, the nitrogen displacement efficiency was low, and a minor quantity of gas remained in the upper corner, the concentration across the holistic working face did steadily decline.

During the later stage of nitrogen injection, nitrogen was continuously injected, and the displacement force of gas was enhanced. Nitrogen occupied the middle and lower regions, further compressing the gas distribution space. This compression forced the gas to concentrate more at the top of the goaf, forming a “dome”-shaped high-concentration gas accumulation zone. The formation of the gas “dome” enrichment zone and the displacement of nitrogen in the middle and lower parts diminished the gas concentration within the working face area to a level beneath the safety threshold. Therefore, the safety of production operations during working face mining is further guaranteed.

Influence of Extraction Negative Pressure on Gas Concentration Distribution

Negative-pressure extraction is the primary technical approach for gas control in the goaf. By

295 combining the displacement and dilution effects of nitrogen and utilizing the extraction negative
296 pressure to guide the gas flow, the mine gas accidents can be effectively lessened. Through the
297 numerical simulation of different extraction negative pressures (5, 10, 15, 20, and 25 kPa), this research
298 investigated how varying extraction negative pressures affected the displacement effect when the
299 nitrogen injection flow rate remained constant.



(a) (b)

Figure 7. The overall distribution of gas in goaf and the data of gas height under different negative pressure of extraction: (**a**) the overall distribution of goaf gas in the process of injection-drainage; and (**b**) line height data map.

300 Figure 6 illustrates the gas distribution state and height development diagram of goaf under
301 different extraction negative pressures. As depicted in Figure 7 (a), while maintaining a fixed nitrogen
302 injection flow rate, the diffusion of nitrogen at the bottom region of the goaf was limited. After a
303 certain period, the displacement effect and the reverse diffusion of gas reached a dynamic equilibrium.
304 Since the extraction hole was positioned above the nitrogen injection hole, it was challenging to disrupt
305 this equilibrium merely by adjusting the extraction negative pressure. Consequently, the gas
306 distribution state on the bottom surface remained unaltered regardless of variations in the extraction

negative pressure. As illustrated in Figure 7 (b), when extraction negative pressure experienced an increase, the gas development height at the 4th and 5th lines increased. In the area near the extraction hole, the increase of negative pressure prominently ameliorated the efficiency of gas extraction, and the high pressure difference accelerated the migration of nitrogen-gas mixed gas to the extraction hole, driving the gas to transfer to the high enrichment area. In the remote area, when the gas concentration was high in the early stage of extraction, the extraction hole was capable of notably decreasing the concentration within the high-concentration region, but with the continuous injection-extraction process, the negative pressure had a limited impact on its local displacement.

In practice, the displacement effect of extraction negative pressure exhibited regional dependence. As the extraction negative pressure increases, the pressure gradient within the goaf rises. This increase promoted the flow of nitrogen-entrained gas towards the low-pressure area (extraction hole) and extended the displacement range. However, the excessive magnitude of negative pressure had the potential to result in the swift extraction of nitrogen, shorten its residence time in the goaf, and curtail the displacement efficiency. Therefore, further research is required to probe the synergistic effect between nitrogen injection and extraction negative pressure, aiming to identify the optimal injection-extraction synergistic parameters.

Gas Migration Law under the Synergistic Effect of Nitrogen Injection and Extraction

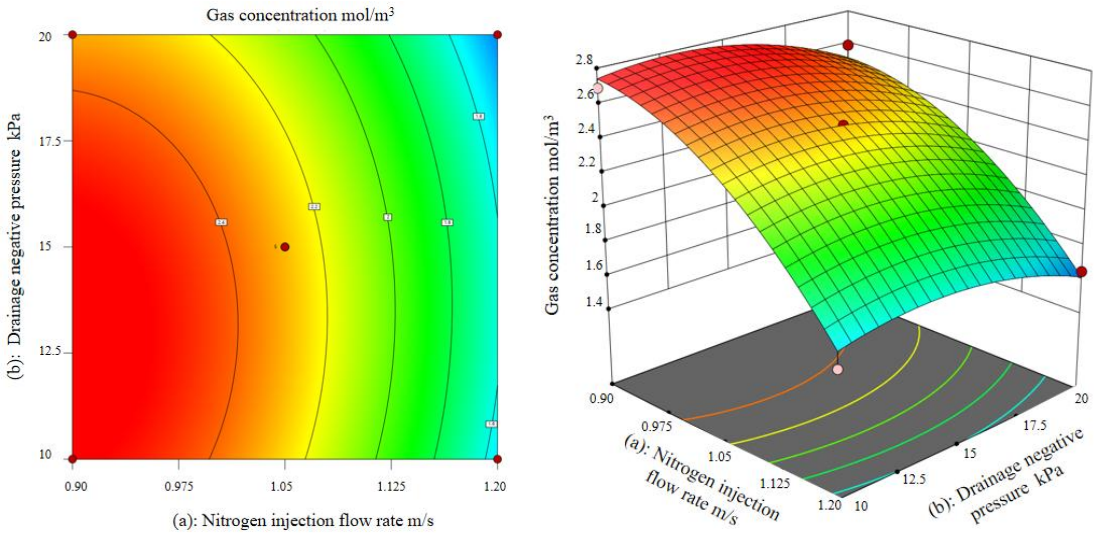
Dynamic Control of Synergistic Effect on Gas Distribution

The central composite design (CCD) was employed to establish the response-surface model for five levels of nitrogen injection flow rate (v) and extraction negative pressure (p). A point within the goaf was selected as the monitoring target for gas concentration changes. The concentration of this fixed point and its associated injection-extraction parameters were designated as the center point of the

response surface. Nitrogen injection flow rate, extraction negative pressure, and gas concentration were considered as the influencing factors for the central composite experiment. The detailed scheme design is presented in Table 1.

Table 1. Scheme design and results

Experimental sequence	Nitrogen injection flow rate（V）	Drainage negative pressure（P）	Response value (gas concentration)
1	0.90	10	2.4882
2	1.20	10	1.4517
3	0.90	20	2.3884
4	1.20	20	1.4482
5	0.75	15	2.5239
6	1.35	15	1.2531
7	1.05	5	2.2583
8	1.05	25	1.8192
9（The center point was repeated 5 times）	1.05	15	2.2882



(a) (b)

Figure 8. Response surface diagram of the influence of nitrogen injection flow rate and extraction negative pressure on gas concentration: (**a**) response surface method plane diagram; and (**b**) response surface method surface schematic diagram.

Figure 8 presents the response-surface diagram depicting the influence of nitrogen injection flow rate and extraction negative pressure on gas concentration. By observing the shape and trend of the surface, it was concluded that when the nitrogen injection flow rate exceeded 1.05 m/s, the gas concentration was more sensitive to the nitrogen injection flow rate, and the surface exhibited a steep downward trend. At this stage, the gas concentration was substantially diminished under the influence of high flow rate, and nitrogen further diluted the gas concentration in the goaf. When the nitrogen injection flow rate was held constant, the surface gradually flattened as the negative pressure increased, which indicated a decrease in the marginal effect of negative pressure on gas concentration. When the flow rate of nitrogen injection surpassed 1.05 m/s and the extraction negative pressure ranges from 10 to 20 kPa, the interaction-term coefficient (A×B) is negative. Under these conditions, the synergistic effect can further decrease the gas concentration, and the synergistic efficiency increases gradually.

Upon nitrogen injection, the “displacement effect” was generated. This effect forces the adsorbed methane to desorb and transform into a free state, while also expanding the gas migration channels. As an inert carrier, nitrogen can mitigate the risk of gas explosion and facilitate its migration towards the low-pressure area (the extraction direction). At this stage, the directional guidance of the extraction negative pressure, by establishing a local low-pressure field, formed the “directional channel” for gas migration and guided the gas to converge at the extraction hole. The synergistic effect of these two factors achieved a dynamic balance between “displacement” and “directional extraction”.

Optimization Model of Collaborative Parameters

The findings obtained from numerical simulations are presented in Table 2, the polynomial

353 regression fitting was performed to derive the regression model with the gas concentration in the goaf
354 as the objective function Eg.(6):

355 $$Y=14.82-19.73A-0.264B+8.27A^2+0.00568B^2-0.0016AB \quad (6)$$

356 In the Eg.(6): A represents is the nitrogen injection flow rate m/s; B is the extraction negative
357 pressure kPa.

358 **Table 2.** Analysis of variance

Source	Degree of freedom	Quadratic sum	Mean square	F ratio	P ratio
Model	5	2.21	0.4429	80.97	< 0.0001
A-Nitrogen injection flow rate	1	1.78	1.78	325.48	< 0.0001
B-Drainage negative pressure	1	0.0656	0.0656	11.99	0.0105
AB	1	0.0023	0.0023	0.4239	0.5359
A^2	1	0.2915	0.2915	53.29	0.0002
B^2	1	0.1168	0.1168	21.35	0.0024
Residual error	7	0.0383	0.0055		
Misfit term	3	0.0383	0.0128	1.595E+06	< 0.0001
Pure error	4	3.200E-08	8.000E-09		
Summation	12	2.25			
R^2		0.9830			
Adjusted R^2		0.9709			

359 Through the process of fitting and validating the regression model presented in Table 2, the R^2 of
360 the prediction model reached 0.983, indicating that the model was reliable and can accurately predict
361 the gas concentration in the goaf corresponding to different nitrogen injection flow rates and extraction

362 negative pressures. As shown in the table under the synergistic effect of injection-extraction, the impact
363 of nitrogen injection flow rate on gas concentration was much higher than that of extraction negative
364 pressure, and its linear influence was higher than that of extraction negative pressure and synergistic
365 effect. Therefore, based on the mathematical fitting model, the optimal parameter values for
366 minimizing the gas concentration were obtained: A synergistic extraction combination of "high flow
367 rate + moderate negative pressure", with a nitrogen injection flow rate of 1.20 m/s and an extraction
368 negative pressure of 20 kPa. Meanwhile, by fitting the approximate linear relationship of *V-P* based on
369 the response-surface contour map, the dynamic matching equation was derived: $V = -0.1P +$
370 $2.4(10 \leq P \leq 20)$.

371 **ENGINEERING PRACTICE**

372 **Process Flow**

373 To address the potential safety hazards posed by gas enrichment in the goaf of high gas and thick
374 coal seam, the dynamic law of gas distribution within the goaf of thick coal seams was revealed
375 through the synergistic effect of nitrogen injection displacement and drainage negative pressure.
376 Furthermore, a set of engineering practice schemes based on a mathematical control model was
377 proposed. According to on the response-surface model and numerical simulation experiments, a
378 matching equation for nitrogen injection velocity (v) and extraction negative pressure (p) was
379 established, quantifying the synergistic effect of these two factors on gas concentration distribution.
380 Nitrogen injection disrupted gas enrichment in the working face by expanding the gas migration range.
381 Meanwhile, the extraction negative pressure directed high-concentration gas towards the extraction
382 port, thereby achieving the "displacement-extraction" synergistic effect.

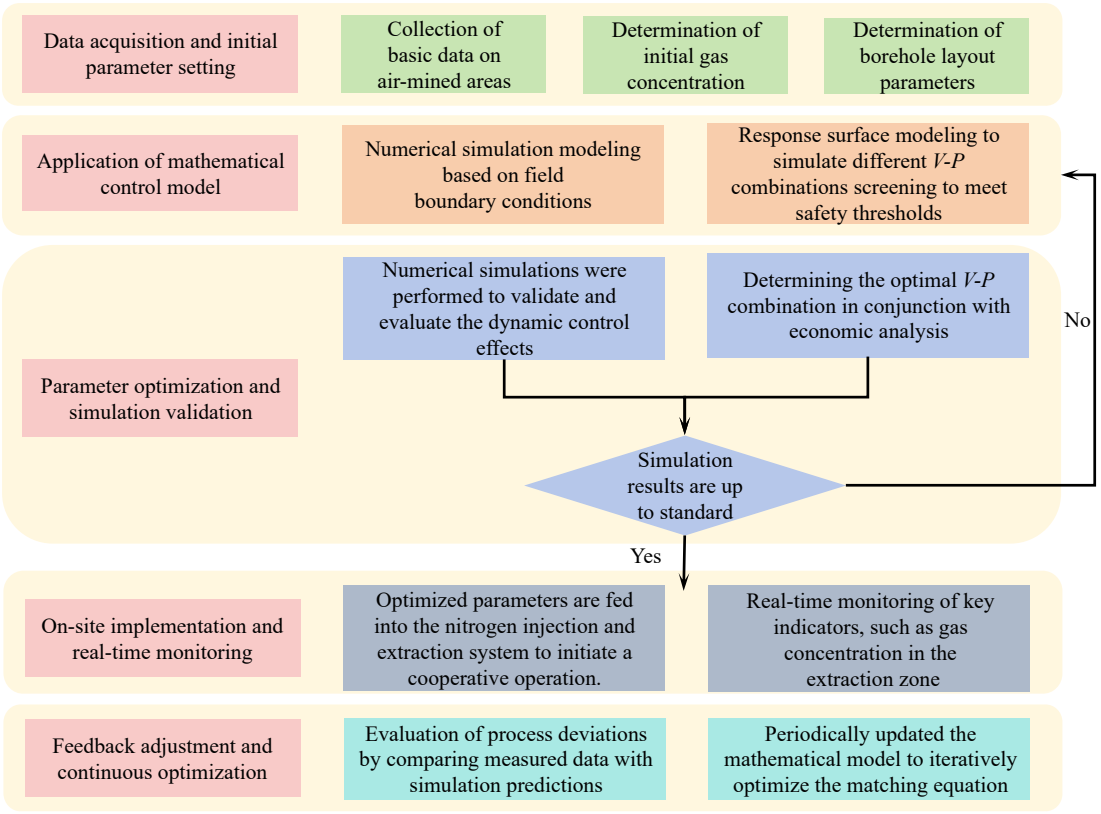


Figure 9. Injection-extraction synergistic process flow.

As depicted in Figure 9, the process flow centered around the numerical simulation and mathematical control model of nitrogen injection - extraction synergy, achieving efficient control of gas distribution via a closed-loop control mechanism. (1) Based on the actual working conditions of goaf, the basic data and borehole layout parameters were gleaned, and the response surface model was employed to predict the gas displacement efficiency of different v-p combinations, and the safety and economic parameter schemes that met the safety threshold are selected. (2) The dynamic control effect of model parameters was verified through numerical simulation to ensure consistency between theoretical results and engineering practice. During the implementation stage, a real-time monitoring system was utilized to dynamically track gas concentration changes and promptly feed back the data to the control model. (3) Through continuous iterative optimization, accurate matching of nitrogen injection and extraction parameters were ensured, effectively inhibiting gas accumulation in the goaf

and guaranteeing the operational safety of the mining face.

Engineering Practice

To quantify the optimization effect of the “nitrogen injection-extraction” process on pressure relief gas extraction efficiency in the goaf of high-gas and thick coal seams, this study analyzed 80-day field - measured data (out of a total of 160 days) from directional drilling extraction before and after nitrogen injection. By integrating a comparative analysis of the injection-extraction collaborative process flow and the mathematical control model, scientific evidence was provided for general practice.

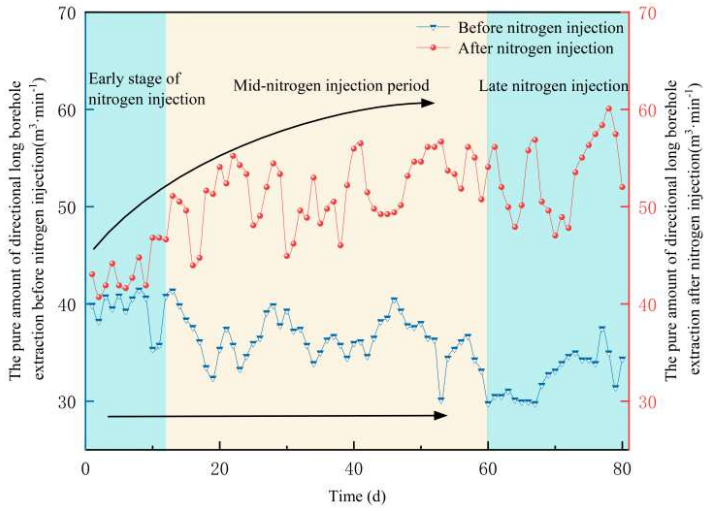


Figure 10. Comparative analysis of gas extraction purity before and after nitrogen injection in directional long borehole.

As illustrated in Figure 10, during the conventional extraction process, the purity of borehole extraction was higher at the initial stage. As extraction progresses, the pure volume of gas extracted from directional long boreholes fluctuated within the range of 30–45 m^3/min and exhibited a downward trend during the 60–80-day period after the start of nitrogen injection. After the beginning of nitrogen injection, nitrogen just entered the goaf in the early stage, and the displacement effect was weak. At this time, the pure amount of borehole extraction was less as a whole. As nitrogen injection continued, the displacement effect of nitrogen within the goaf became increasingly noteworthy. The pure volume of extraction increased to 40–60 m^3/min and persisted at an elevated level in the latter stage of nitrogen

injection.

Comprehensive analysis revealed that the “nitrogen injection-extraction” process enhanced gas extraction efficiency in the goaf by 36%. This improvement was achieved by augmenting the synergistic effect between the gas migration range and the directional guidance of the extraction negative pressure. Under the dynamic feedback mechanism, the optimized parameters (V=1.20 m/s，P=20 kPa) selected by the mathematical control model realize the long-term control of the deep gas enrichment area (the extraction volume is still stable above 50 m^3/min after 60 days). Upon nitrogen injection, high-concentration gas was guided towards the extraction port, effectively disrupting local gas accumulation. The research results validated the engineering applicability of the “nitrogen injection-extraction” collaborative process. The closed-loop control logic enabled the precise control of gas distribution and ensures the safety of the mining face. It can provide theoretical support and process guidance for the safe mining of similar high-gas coal seams, and further enhanced the universality and economic viability of the process.

CONCLUSIONS

Through this study, three conclusions were drawn as follows:

1. Numerical simulations determined the gas distribution state in the goaf under various nitrogen injection flow rates and extraction negative pressures. As the nitrogen injection flow rate increased, the penetration depth and displacement range of nitrogen were enhanced. The maximum displacement distance along the bottom of the goaf reached 140.2 m, forming an “air cushion”, forcing low-density methane to float up and accumulate at the top, forming a “dome” shape. The reasonable combination of extraction negative pressure broke the balance of local gas accumulation by guiding the gas migration path directionally.

2. A regression model was constructed and variance analysis was performed using the central composite design, with a coefficient of determination R^2 of 0.983. Confirmation of the model's reliability was achieved, and the dominant role of the nitrogen injection flow rate in affecting gas concentration was determined. In addition, it was found that the marginal effect of negative pressure diminished as the pressure increases. The synergistic effect of the two was used to quantify the dynamic matching equation (v=–0.1p+2.4), which revealed the synergistic mechanism of "nitrogen injection-extraction" and served as a theoretical foundation for the optimization of engineering parameters.

3. In the course of the working face's mining operation, compared with the pure amount of gas extraction before and after nitrogen injection, the average value of the pure extraction amount showed growth by 36%, and the high-efficiency extraction was still maintained in the later stage of nitrogen injection, and extraction amount was stable above 50 m^3/min for a long time. The process mitigated the risk of mine gas accidents by inhibiting deep-seated gas accumulation and directionally guiding gas to the upper region of the goaf, thereby forming a "dome"-shaped structure at the top. Meanwhile, through the dynamic iterative optimization of the mathematical model, this process offered a safe and economical solution for the mining of high-gas thick coal seams, demonstrating broad engineering application value.

ACKNOWLEDGMENTS

This work was financially supported by the National Key Research and Development Program (2023YFC3009004-6); Open project of Key Laboratory of Ministry of Education of Xinjiang Coal Resources Green Mining (KLXGY-KA2404); Xinjiang Uygur Autonomous Region Key R&D Task Special Program(2025B03038-2); Shaanxi key R&D project (2024GX-YBXM-490); Shaanxi

Provincial Natural Science Basic Research Program General Project-Youth Project (2025JC-YBQN-657); National Natural Science Foundation of China (52174205); The Natural Science Basic Research Program of Shaanxi Province under Grant (2025JC-YBMS-491); National Natural Science Foundation of China (52204235).

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

[1] K. Gao, S. Ma, Optimized layout for high-level drilling in a high-gas coal seam to prevent gas overrun. Processes. 13 (2025) 688. https://doi.org/10.3390/pr13030688

[2] R. S. Zhuo, P. X. Zhao, X. Y. Sun, S. G. Li, Y. Y. Jia, H. Liu, W. D. Lu, J. S. Yang, Y. J. Liu, Microseismic monitoring energy and GHG emission correlation assessment of extremely thick coal seam mining in China. Journal of Environmental Chemical Engineering. 13 (2025) 116292-116308. https://doi.org/10.1016/j.jece.2025.116292

[3] Z. Li, L. Wang, X. Xie, R. K. Pan, X. H. Wang, N_2 inhibition characteristics of coal spontaneous combustion in goaf: experimental study and numerical analysis. Combustion Science and Technology. 196 (2024) 4220-4241. https://doi.org/10.1080/00102202.2023.2206962

[4] S. G. Li, C. Z. Wang,B. Zhou, H. Q. Shuang, H. F. Lin, S. J. Peng, B. Hu, H. Yang, H. Liu, Deformation and seepage characteristics of gassy coal subjected to cyclic loading–unloading of pore pressure. Natural Resources Research. 34 (2025) 2775–2796. DOI:10.1007/s11053-025-10541-7.

[5] Aitao. Z, Kai. W, A new gas extraction technique for high-gas multi-seam mining: a case study in

Yangquan Coalfield, China. Environmental Earth Sciences. 77 (2018) 1-16. https://doi.org/10.1007/s12665-018-7291-z

[6] C. Z. Wang, B. Zhou, S. G. Li, H. F. Lin, H. Q. Shuang, D. M. Zhang, S. J. Peng, L. Cheng, H. Yang, Dominant governing mechanisms of deformation-seepage and dynamic evolution model of permeability in gas-containing coal under coupled stress-pore pressure. Fuel, 404 (2025) 136408. DOI: 10.1016/j.fuel.2025.136408.

[7] S. Kong, Y. Cheng, T. Ren, H. Y. Liu, A sequential approach to control gas for the extraction of multi-gassy coal seams from traditional gas well drainage to mining-induced stress relief. Applied Energy. 131 (2014) 67-78. https://doi.org/10.1016/j.apenergy.2014.06.015

[8] R. S. Zhuo, P. X. Zhao, X. Y. Sun, S. G. Li, H. Liu, Y. Y. Jia, L. L. Wang, Y. J. Liu, A COMSOL simulation of fracture-stress-seepage coupling during extremely thick coal seam mining. Engineering Fracture Mechanics. 326 (2025) 111407. https://doi.org/10.1016/j.engfracmech.2025.111407

[9] J. Chai, Study on gas control in goaf of high gas coal seam: A case study of tingnan coal mine, China. Geofluids. 2022 (2022) 5262173. https://doi.org/=10.1155/2022/5262173

[10] Z. Shi, D. Ye, J. Hao, B. Qin, G. Li, Research on gas extraction and cut flow technology for lower slice pressure relief gas under slice mining of extra-thick coal seam. ACS Omega. 7 (2022) 24531-24550. https://doi.org/10.1021/acsomega.2c02255

[11] C. Cheng, X. Y. Cheng, L. Chen, X. Y. Ma, Research on gas control technology in goaf based on the influence of mining speed. Processes. 12 (2024) 1528. https://doi.org/10.3390/pr12071528

[12] P. X. Zhao, R. S. Zhuo, S. G. Li, C. M. Shu, L. W. Bin, Y. Y. Jia, Y. Shi, L. Suo, Analysis of advancing speed effect in gas safety extraction channels and pressure-relief gas extraction. Fuel.

265 (2023) 116825. https://doi.org/10.1016/j.fuel.2019.116825

[13] R. S. Zhuo, P. X. Zhao, S.G. Li, H. F. Lin, H. Liu, X. G. Kong, S. K. Jin, Z. Wang, Q. Jin, Effects of coal thickness on the fractal dimension of gas migration channels: laboratory and field study of a gassy coal mine. Natural Resources Research. 33 (2024) 1193-1208. https://doi.org/10.1016/j.fuel.2019.116825

[14] P. X. Zhao, J. A. Wang, S. H. Li, H. Li, L. Qin, H. F. Lin, C. M. Shu, L. W. Bin, Y. Y. Jia, Z. Y. Wei, W. B. Pei, Effects of recovery ratio on the fracture evolution of the overburden pressure-relief gas migration channel for a fully mechanized working face. Natural Resources Research. 31 (2022) 1011-1026. https://doi.org/10.1007/s11053-021-09993-4

[15] L. Y. Shu, Study on gas extraction technology for goaf using L-shaped borehole on the ground. Applied Sciences. 14 (2024) 1594. https://doi.org/10.3390/app14041594

[16] F. Li, Y. Shang, D. Kong, G. Zhang, Y. Wang, Y. Wang, Z. Zhang, Gas migration law and precision extraction in close distance coal seam goaf: a case study. Geotechnical and Geological Engineering. 41 (2023) 3781-3801. https://doi.org/10.1007/s10706-023-02489-3

[17] C. Liu, Optimizing methane control in composite goaf areas: Insights from multisource emission analysis and numerical modeling in the Tongxin coal mine. ACS Omega. 9 (2024) 41171-41178. https://doi.org/10.1021/acsomega.4c01389

[18] L. Zhang, M. Yang, H. Luo, Parameter optimization and application of gas extraction technology by buried pipes in goaf of multi-roadway U-type working face. Combustion Science and Technology. 196 (2024) 820-837. https://doi.org/10.1080/00102202.2022.2101367

[19] H. Jia, Z. Wang, X. Zhao, S. J. Ma, Z. R. Song, J. P. Chen, Characterization of spatiotemporal distribution of gas in the goaf of W-type ventilated working face. Process Safety and

Environmental Protection. 184 (2024) 1379-1388. https://doi.org/10.1016/j.psep.2024.02.048

[20] L. Wang, J. T . Li, J. Y. Fan, C. Y. Sun, J. H. Zhang, J. L. Zhang, Influence of gas extraction process elements on the gas migration law in high-gas goaf areas. ACS Omega,10 (2025) 3090-3100 https://doi.org/10.1021/acsomega.4c09962

[21] Z. Qian, Research on multi-directional gas drainage technology in goaf of working face. IOP Conference Series: Earth and Environmental Science. IOP Publishing. 526 (2020) 012167. https://doi.org/10.1088/1755-1315/526/1/012167

[22] S. F. Lyu, Y. H. Xiao, C. Chen L. Z. K. Xiong, S. S. Wang, Enhancement of coalbed methane via nitrogen injection in a coal mining area: A laboratory and field study. Journal of Energy Engineering. 149 (2023) 04023047. https://doi.org/10.1061/JLEED9.EYENG-4936

[23] R. Z. Hu, G. Wang, Y. H. Wang, I. Canbulat, G. Y. Si, From dynamic goaf formation to evolving spontaneous combustion and gas explosion hazard management. Process Safety and Environmental Protection. (2025) 107131. https://doi.org/10.1016/j.psep.2025.107131

[24] L. Zhang, C. M. Wei, Y. Nie, R. Y. Wang, Pressure measurement of coal seam with active nitrogen injection: Model and experimental analysis. ACS Omega. 7 (2022) 46935-46945. https://doi.org/10.1021/acsomega.2c06012

[25] P. F. Ji, H. F. Lin, X. G. Kong, S. G. Li, Y. C. Cai, R. Z. Wang, Y. Tian, T. S. Zhao, Experimental study on enhanced coal seam gas extraction by uniform pressure/pulse pressure N_2 injection. Fuel. 351 (2023) 128988. https://doi.org/10.1016/j.fuel.2023.128988

[26] L. Z. Chen, X. Y. Qi, Y. D. Li, H. H. Xin, Z. Q. Liang, Coupling relation between the location of cross-cut negative pressure and injecting nitrogen into coal mine goaf. ACS Omega. 6 (2021) 8189-8198.https://doi.org/10.1021/acsomega.0c06222

546 [27] H. R. Gong, K. Wang, G. D. Wang, X. Yang, F. Du, Underground coal seam gas displacement
547 by injecting nitrogen: Field test and effect prediction. Fuel. 306 (2021) 121646.
548 https://doi.org/10.1016/j.fuel.2021.121646
549 [28] H. Liu, Z. B. Li, H. Wang, M. N. Chen, L. Xian, Numerical simulation investigation of N_2
550 injection for enhanced coalbed methane recovery. Arabian Journal for Science and Engineering.
551 (2024) 1-12. https://doi.org/10.1007/s13369-024-09123-1
552 [29] L. Wang, Z. L. Deng, X. L. Wang, Z. F. Wang, L. S. Hu, P. T. Zhao, Mechanisms of methane
553 displacement by CO_2/N_2 injection in tectonic coal under different gas-driving modes. Natural
554 Resources Research. 33 (2024) 405-420. https://doi.org/10.1007/s11053-023-10288-z
555 [30] Y. Shi, B. Q. Lin, T. Liu, M. Chen, J. Kong, M. H. Lin, W. Yang, Modeling and optimization of
556 recovery enhancement efficiency by CO_2/N_2 mixture displacement in stimulated coal seams by
557 destressing boreholes. Geoenergy Science and Engineering. 221 (2023) 211371.
558 https://doi.org/10.1016/j.geoen.2022.211371
559 [31] H. O. Wen, C. J. Fan, X. F. Jiang, M. K. Luo, B. Xiao, L. J. Zhou, Z. H. Yang, Experimental
560 investigations on enhanced coal seam methane extraction by injecting gas: A review. Energy &
561 Fuels. 38 (2024) 3517-3538. https://doi.org/10.1021/acs.energyfuels.3c04121
562 [32] Liang．Y, Theory and practice of integrated coal production and gas extraction. International
563 Journal of Coal Science & Technology. 2 (2015) 3-11.
564 [33] Z. X. Li, S. L. Ji, Z. Y. Ti, Gas-atmospheric two-phase miscible diffusion model in goaf and its
565 solution. Journal of Rock Mechanics and Engineering. 16 (2005) 2971-2976.
566 [34] T. H. Yang, S. K. Chen, W. C. Zhu, Z. G. Huo, W. Z. Jiang, Nonlinear seepage-diffusion model
567 of gas in caving zone and its solution. Journal of Coal. 34 (2009). 771-777.