Research on Gas Extraction and Cut Flow Technology for Lower Slice Pressure Relief Gas under Slice Mining of Extra-thick Coal Seam

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ABSTRACT: For extra-thick coal seams, slice mining is a safer mining method than top coal mining, which can effectively reduce the strong mine pressure behavior caused by mining. However, in the slice mining of high-gas and extra-thick coal seams, the gas in the lower slice flows into the goaf, which increases the gas control difficulty on the upper slice working face. It is easy to cause the gas transfinite at the upper corner in the upper slice and reduce the mining efficiency. Therefore, it is of a great significance to carry out the research on gas control technology in slice mining of the extra-thick coal seam. There are some problems in the gas control of slice mining, such as a single gas control method, low control efficiency, and unclear gas migration law. Therefore, it is necessary to study the gas migration law and propose a targeted prevention and control the technical scheme.

In order to improve the gas control efficiency of the extra-thick coal seam, the evolution law of permeability of the lower slice is obtained under mining through experimental research. The liquid−solid coupling seepage-flow model for gas migration is established in the lower slice. Comsol Multiphysics software is used to study the migration law of pressure relief gas in the lower slice. Based on the gas migration law, the gas extraction and cut flow technology for the lower slice long borehole is proposed. Through this technology, the amount of gas flowing into the upper slice goaf and the gas content of the lower slice are reduced, and the drilling horizon is optimized. The research results show that the determination of the optimal drilling horizon of the lower slice is obtained under mining through experimental research. The liquid−solid coupling seepage-flow model for gas migration is established in the lower slice. Comsol Multiphysics software is used to study the migration law of pressure relief gas in the lower slice. Based on the gas migration law, the gas extraction and cut flow technology for the lower slice long borehole is proposed. Through this technology, the amount of gas flowing into the upper slice goaf and the gas content of the lower slice are reduced, and the drilling horizon is optimized. The research results show that the determination of the optimal drilling horizon of the lower slice is obtained under mining through experimental research.

1. INTRODUCTION

Gas prevention is an important guarantee for safe and efficient production in mines, and as the mining depth increases, coal mining will face more and more gas prevention problems in the future.1−4 At present, various technologies have been developed for gas extraction, such as coal seam preextraction, pressure relief gas drainage in the adjacent layer, bottom drainage roadway extraction, high alley pumping extraction, high level borehole extraction, goaf buried pipe extraction, large diameter drilling extraction, and so forth. The gas drainage technology and gas migration law complement each other.5−12 Thick and high-gas coal seams are widespread in the United States, Australia, and China.13−16 However, there are a few pieces of research on the gas extraction technology for slice mining of extra-thick coal seams that need to be carried out.

At present, a large number of studies have been carried out on the gas migration law and extraction technology of thick coal seams, ones mining full height and top coal caving.17−26 The extraction technology mainly considers the migration law of pressure relief gas in the overburden fissures and the mission law of the working face. In the study of the gas extraction technology in slice mining, Gao et al.27 used a numerical simulation to study the stress and failure characteristics of the lower slice under a steep coal seam, obtaining the damage depth and influence law of the dip angle. Li et al.28 obtained the in situ stress distribution law of the deep mine. Shi et al.29 proposed the pressure relief gas extraction technology using lower slice long drilling holes under extra-thick coal seams and
analyzed the stability affecting factors of drilling holes in a different horizon. Fan et al. explored the seepage characteristics of bottom coal gas, coal deformation, and the gas permeability evolution law of four coal samples in different stress zones of the bottom coal of the working face through true triaxial fluid–solid coupling seepage experiments. Liu et al. used comprehensive methods including theoretical calculation, similar simulation, and numerical simulation to analyze the failure laws of the lower slice along the strike and depth during the top slice mining process. Wang et al. analyzed and evaluated the effects based on the gas control application of the introduced directional drilling equipment and techniques in Chinese thick coal mines. Huang et al. studied the permeability characteristics of the lower slice after upper slice mining based on the udec software. Xuchao et al. established the gas emission prediction model under slice mining. Zhao et al. analyzed distribution characteristics of gas migration channels under different mining heights. Fan et al. considered the combined effects of gas slippage and the two-phase flow and proposed a hydraulic–mechanical coupling model for gas migration and simulated the hydraulic punching process of floor roadway.

The above research is in the field of slice mining of thick coal seams, and most studies are above failure of the lower slice coal body and the evolution law of the fracture channel of the roof layer. There are few studies on the gas migration law after the destruction of the lower slice coal body. Also, in the gas control plan, the method of extraction and cut flow based on the gas migration law is not proposed. The proposed extraction technology needs to be further optimized. Therefore, taking the slice mining conditions of extra-thick coal seams as the background, this paper investigates the gas migration law of the lower slice after upper slice mining. The extraction and cut flow technology of long boreholes are innovatively proposed, which are arranged in the lower slice. Also, according to the extraction effect of different horizons, the drilling horizons are optimized.

2. EVOLUTION LAW OF PERMEABILITY OF THE LOWER SLICE UNDER SLICE MINING

2.1. Experiment on the Evolution Law of Coal Seam Permeability under Mining Action. Before the lower slice mining, the lower slice coal experienced a mining stress effect. In order to obtain the permeability evolution law under the effect of the mining stress, seepage experimental research was carried out based on mining stress path loading.

2.1.1. Experimental Installation. The test device mainly includes four parts: the stress loading system is mainly composed of a press, a seepage stress cavity, and a pressure supply pump. The press provides axial pressure, and the supply pressure pump provides confining pressure. The seepage stress cavity realizes the sealing and fixing of coal samples. The gas pore pressure loading system is mainly composed of a gas cylinder, a pressure regulating valve, and a pressure gauge. The gas cylinder provides seepage gas, the pressure regulating valve realizes a stable pore pressure, and the pressure gauge reads the pore pressure. The coal sample deformation measurement system is mainly composed of foil strain gauges, a data

Figure 1. Schematic diagram of the experimental device structure.

Figure 2. Preparation of experimental coal samples.
acquisition instrument, and a computer. The foil strain gauges measure the axial and horizontal deformation of coal samples, and the data acquisition instrument and computer realize the storage of deformation amounts. The flow monitoring system is mainly composed of a measuring cylinder and a water container. The gas volume is obtained by the drainage method, and the flow is obtained by the volume-to-exhaust time ratio, as shown in Figures 1 and 2.

### 2.1.2. Loading Path

#### 2.1.2.1. Model Establishment and Boundary Conditions

The loading path is obtained by a numerical calculation based on the geological and production conditions of the working face, and the numerical simulation was carried out using FLAC3D. The model rock layer is simplified to 10 layers and is based on the working face pressure display step distance, which is obtained by field measurement, and a calculation model with a size of 300 m (x) × 300 m (y) × 160 m (z) is established, so that the numerical simulation can reach the same rock stratum movement state as the field. The working face is in the 4# coal seam, and the coal seam is near the horizontal. In order to facilitate the calculation, the inclination of the coal seam is set to 0°. The Mohr-Coulomb model is adopted. The depth of simulation working face is 480 m. The height of the model roof is 100 m. The upper surface of the model is 380 m from the surface, and the applied load is 9.5 MPa. The front, rear, left, and right sides of the model constrain normal freedom degrees, and the bottom surface constrains the freedom degrees of the directions x, y, and z. The numerical calculation model is shown in Figure 3, and the physical mechanical parameters of the rock formation are shown in Table 1.

#### 2.1.2.2. Stress Monitoring Design

Stress monitoring points are established in the numerical model to monitor the evolution law of mining stress and the scope of the “O”-ring pressure relief area on the return airway of the working face. The layout of the measuring points is shown in Figure 4. The measuring point is 75 m away from the open cut, and this point is located in the design stress monitoring zone. The measuring point is 75 m away from the open cut, and this point is located in the design stress monitoring zone.

### Table 1. Physicomechanical Parameters of Coal and Rock Layers

| lithology                | bulk modulus/GPa | shear modulus/GPa | density/(kg·m\(^{-3}\)) | Cohesion/MPa | friction angle/deg | tensile strength/MPa |
|-------------------------|------------------|-------------------|--------------------------|--------------|--------------------|----------------------|
| overburden 10           | 4.60             | 4.45              | 2500                     | 3.50         | 38                 | 1.35                 |
| coarse sandstone 9      | 4.53             | 4.37              | 2510                     | 2.53         | 34                 | 1.26                 |
| fine sandstone 8        | 4.64             | 4.32              | 2540                     | 4.57         | 35                 | 1.35                 |
| coarse sandstone 7      | 4.58             | 4.42              | 2530                     | 2.57         | 34                 | 1.28                 |
| mudstone 6              | 4.54             | 4.31              | 2560                     | 2.08         | 32                 | 1.32                 |
| upper slice coal seam 5 | 1.42             | 0.57              | 1400                     | 1.20         | 20                 | 0.64                 |
| lower slice coal seam 4 | 1.42             | 0.57              | 1400                     | 1.20         | 20                 | 0.64                 |
| aluminous mudstone 3    | 4.87             | 4.79              | 2420                     | 1.76         | 39                 | 1.31                 |
| sandy mudstone 2        | 4.52             | 4.34              | 2560                     | 2.08         | 36                 | 1.35                 |
| siltstone 1             | 4.67             | 4.53              | 2550                     | 4.58         | 39                 | 1.42                 |
distance can meet the periodic pressure. At this time, the evolution law of mining stress is stable, which can reflect the loading and unloading effect of mining stress on the lower slice. The inclination measuring point is located in the middle of the stope strike, which can reflect the distribution range of the “O”-ring pressure relief area.

2.1.2.3. Loading Path of Lower Slice Coal and Range of the “O” Ring. For extracting the vertical stress and horizontal stress of the toward stress monitoring points as the working face advances, the loading path of the lower slice coal is shown in Figure 5. After the mining is completed, for extracting the vertical stress and horizontal stress are selected as the axial and confining pressure loading values, implementing a simulation of the mining effect. The mining process is given as shown in Figure 4. The serial numbers 1 → 13 in the figure represent the stress value evolution of the axial pressure and the confining pressure during the mining process. The parameters of the axial pressure and confining pressure can be selected according to Figure 7. According to Figure 6, it can be obtained that the “O” ring pressure relief range is about 50 m, and the location of the extraction drilling should be selected within 50 m of the return airway.

2.1.3. Experimental Procedure. Step 1: In the experiment, the confining pressure is loaded by a manual pump. The loading speed is slow and takes a long time. Therefore, the confining pressure loading time is reserved during the experiment. At the same time, due to the high level of static pressure, the initial axial pressure is 12 MPa, and the confining pressure is 7 MPa. In order to ensure that the coal sample is not damaged in the process of loading to the static pressure level, a gradient loading method is adopted. Loading to the static pressure level: first, the axial pressure is loaded to 2 MPa, then loading the confining pressure to 3 MPa, then loading the axial pressure to 6 MPa, then loading the confining pressure to 7 MPa, and finally loading the axial pressure to 12 MPa.

Step 2: The axial pressure and confining pressure are changed successively as 7, 12, 7.5, 13.5, 8, 14, 8.5, 16, 9, 17, 9.5, 18, 9, 16.5, 8, 15, 7, 13, 6, 11, 5, 7.5, 5, 7.53, and 6. The axial pressure loading speed is 50 N/s, when the axial pressure and confining pressure is constant, the pore pressure is loaded to 2.5 MPa, and the flow rate of the outgoing gas is measured.

2.2. Results. 2.2.1. Experimental Data. Figure 8 shows the variation law of permeability with loading and unloading. The axial pressure increases from 12 to 18 MPa, and the confining pressure increases from 7 to 9.5 MPa. The permeability of coal samples decreases gradually from 0.007 to 0.001 mD. The axial pressure decreases from 18 to 5 MPa, and the confining pressure decreases from 9.5 to 3 MPa, and the coal samples permeability increase gradually from 0.001 to 0.0194 mD.

2.2.2. Establishment of the Permeability Model. Figure 8 shows the variation law of coal sample permeability under different axial and confining pressures, and the permeability
reflects the difficulty of gas migration and extraction in the coal seam. The permeability has an exponential relationship with the ground stress, the swelling stress of adsorption, and the pore pressure. The relationship is shown in formula 1

$$k = e^{-A\sigma - B\sigma_1 + Cp}$$  \hspace{1cm} (1)

where \(k\) is permeability, mD; \(A, B, C\) are permeability fitting constants; \(\sigma\) is volume stress, MPa; \(\sigma_1\) is swelling stress of adsorption, MPa; \(p\) is pore pressure, MPa.

The experimentally measured stress pore pressure permeability data are shown in Table 2.

Table 2 shows that the change in permeability during the unloading stage under the mining effect. Since the floor extraction drilling is arranged in the lower slice, the permeability distribution law of the lower slice is obtained, which has a practical significance for the selection of drilling layers.

According to formula 1, the volume stress \(\sigma\) and swelling stress of adsorption \(\sigma_1\) shall be calculated

$$\sigma = \sigma_x + 2\sigma_z$$  \hspace{1cm} (2)

$$\sigma_1 = \frac{2\rho RTa(1 - 2\nu)}{3V_m} \ln(1 + bp)$$  \hspace{1cm} (3)

where \(\sigma_x\) is vertical stress; \(\sigma_z\) is horizontal stress; \(E\) is coal matrix elastic modulus, Pa; \(\epsilon_p\) is single direction swelling strain. \(\rho\) is coal apparent density, kg/m\(^3\); \(R\) is molar gas constant, J/(mol·K); \(T\) is adsorption ambient temperature, K; \(a\) is ultimate adsorption capacity of the unit mass coal matrix under reference pressure, m\(^3\)/t; \(b\) is the adsorption equilibrium constant, MPa\(^{-1}\); \(\nu\) is the coal matrix Poisson’s ratio; \(V_m\) is the gas molar volume, L/mol.

According to formulas 2 and 3 and Table 2, the volume stress, pore pressure, and swelling stress of adsorption are calculated, as shown in Table 3.

Using eq 1 to fit the data in Table 3, the calculation formula of permeability with volume stress, swelling stress of adsorption, and pore pressure is show in formula 4

$$k = e^{-0.138\sigma - 10\sigma_1 + 1.4p}$$  \hspace{1cm} (4)

3. ESTABLISHMENT OF A FLUID–SOLID-COUPL ED MODEL FOR GAS MIGRATION IN THE LOWER SLICE

3.1. Governing Equation of the Stress Field and Deformation Field of Coal and Rock Mass. 3.1.1. Analysis of Volume Stress in Different Layers of the Lower Slice. Based on the FLAC3D numerical simulation results, the horizontal stress and vertical stress of different layers are obtained in Figure 9.

Figure 9. Stress of different horizons of the Tingnan mine.
Based on the fitting results in Figure 9, the volume stress at different horizons is

$$\sigma = 2\sigma_z + \sigma_i = 1.069z^{1.16}$$  \hspace{1cm} (5)$$

where $z$ is the distance to the goaf floor, m.

3.1.2. Deformation Control Equation of Coal and Rock Mass. The total stress of coal and rock mass includes the pore pressure, swelling stress of adsorption, and ground stress. According to the elastic mechanics theory, the constitutive equation, the equilibrium equation, and the geometric equation are established, considering which the effective stress and the deformation control equation of coal containing methane is obtained, which can be abbreviated by the tensor algorithm as

$$Gu_{ij,j} + \frac{G}{2\nu}u_{ij,j} + \alpha p_{r,i} + \frac{2\rho RTa}{3V_m}(1 - 2\nu)\ln(1 + bp)_{,i}$$

$$+ F_i = 0$$  \hspace{1cm} (6)$$

where $G$ is the shear modulus, MPa; $\nu$ is the displacement component, m; $\alpha$ is the Biot coefficient, $\alpha = 1 - K/K_s$, $K_s$ is the bulk modulus of the coal skeleton, MPa; $K$ is the bulk modulus of coal, MPa; $F$ is the volume force, N/m$^3$; $i, j = 1, 2, 3$.

3.2. Governing Equation of the Seepage Field of Coal and Rock Mass. The coal seam is regarded as dual media, which is composed of pores and fractures. The fractures and pores in coal seams are saturated with a single-phase gas. Also, the gas in the coal seam exists in absorption and desorption states. The gas migration in coal seams conforms to the Darcy equation

$$V = \frac{k}{\mu} \nabla p$$  \hspace{1cm} (7)$$

where $V$ is Darcy seepage velocity, m/s; $\mu$ is the gas kinematic coefficient of viscosity, Pa·s; $\nabla p$ is the coal seam gas pressure gradient, Pa/m.

According to the continuity equation of gas seepage and coal-rock skeleton, the continuity equation of gas seepage in the coal seam is deduced as eq 8

$$\frac{\partial \rho_g}{\partial t} + \rho_g \cdot \nabla V + (1 - \phi)\rho_s \frac{\partial \varepsilon_v}{\partial t} + \nabla \cdot (\rho_g V) = q_m$$  \hspace{1cm} (8)$$

where $\rho_g$ is the gas density, kg/m$^3$; $\rho_s$ is the coal skeleton density, kg/m$^3$; $\phi$ is the porosity; $t$ is the time; $\varepsilon_v$ is the volumetric strain; $q_m$ is the mass source, kg/(m$^3$·s).

In the elastic deformation range, when the gas pressure difference changes little, the porosity can be expressed as

$$\phi = \phi_0[1 + C_\phi(p - p_i)]$$  \hspace{1cm} (9)$$

where $C_\phi$ is the pore compressibility, MPa$^{-1}$; $\phi_0$ is the initial porosity; $p_i$ is the initial pore pressure, MPa.

From the experimental results of the permeability variation under the action of the mining stress, it can be seen that the permeability has an exponential relationship with the ground stress, swelling stress of adsorption, and pore pressure. The fitting equation is

$$k_s = e^{-\Lambda_0 - 8\sigma_i + C_\phi}$$  \hspace{1cm} (10)$$

By substituting Darcy’s law, the gas state equation, and the porosity equation into eq 8, the governing equation of gas seepage in the coal seam is obtained as eq 11

$$p \frac{\partial V}{\partial t} + \left[\phi + \frac{\rho_0}{\rho} E(1 - \phi)\right] \frac{\partial p}{\partial t} + \nabla \cdot \left(p \frac{k}{\mu} \nabla p\right) = \frac{RT}{M}q_m$$  \hspace{1cm} (11)$$

where $\rho_0$ is the initial coal skeleton density, kg/m$^3$; $M$ is the molar mass of the gas, kg/mol.

4. RESEARCH ON GAS EXTRACTION AND CUT FLOW TECHNOLOGY FOR THE LOWER SLICE PRESSURE RELIEF GAS

4.1. Engineering Background. 4.1.1. Working Face Situation. The average thickness of 205 working face in the Tingnan Coal Mine is 19 m, which belongs to the extra-thick coal seam with an average dip angle of 4°. The coal property is relatively hard with a high mechanical strength, and the f value is 1.95–2.7, which is beneficial to the stability of horizontal long boreholes. The working face uses the slice mining method. The upper slice height mining is 6 m, and the lower slice height mining is 13 m. The upper slice adopts the fully caving method to manage the roof. The monthly working face advance is 120–180 m. The average daily advance is 4–6 m, and the monthly output of the working face is about 9210 t. The 205 working face gas content is 4.3 m$^3$/t, and the gas pressure is 0.6 MPa. After the upper slice mines, around the goaf forms an “O”-ring pressure relief area. The pressure relief area caving and compaction is not completely, and the permeability is high. The lower slice pressure relief gas is easy for emission into the upper slice working face. Therefore, the extraction and cut flow long boreholes are designed in this area of the lower slice.

4.1.2. Extraction Borehole Design and Construction Technology. After the 205 working face is formed, the ZDY12000LD directional drilling rig is used to construct the
directional borehole. In the 205 working face, 4 drilling sites are set up to drill holes at the −3, −6, −9, and −12 m layers, and 5 holes are constructed in each layer. According to the scope of the "O" ring, the tendency range of the drilling holes arrangement is the return airway points within 50 m of the working face. The drilling holes distribution is shown in Figure 10.

Each drilling group consists of a main hole and four branch holes. The preliminary design of the branch hole spacing is 8 m. The design of hole spacing at the same level is mainly determined by the drainage radius, and the purpose is to ensure that the extraction radius of adjacent boreholes can be tangent or coincident so as to fully cover the gas emission area of the lower slice. According to the field test results of the drainage radius, the drainage radius is 4 m. Therefore, the horizontal spacing of the holes is designed as 8 m in the design. The parameters of the four drilling groups are shown in Table 4.

The trajectory design scheme of each borehole in the drill site is shown in Figure 11.

The designed hole diameter of the test holes is 150 mm. In order to meet this requirement, the holes reaming method is adopted. First, a Φ120 mm pilot hole is constructed, and then the hole is reamed to Φ150 mm at one time. When the pilot hole is constructed, a Φ89 mm center cable drill pipe is used to match the YHD2-1000 (A) wired measuring trajectory device. The hole diameter is 120 mm, and the drill is lifted after the designed hole depth is reached, and then the Φ89 mm outer flat drill pipe is used to match the Φ150 mm reaming bit for reaming to achieve the construction goal.

4.1.3. Main Influencing Factors in the Long Boreholes Arrangement in the Lower Slice. In the borehole arrangement, in addition to considering the gas migration law, it should also consider whether the borehole will not be damaged under the mining stress. At the same time, it is necessary to consider the length of the borehole and the negative pressure.

4.1.3.1. Borehole Horizon. The borehole horizon determines the gas interception effect and the gas drainage effect on the lower slice. The borehole arrangement close to the goaf enhances the interception effect, but the predrainage effect is weakened on the lower slice. The layer layout needs to comprehensively consider the above relationship.

4.1.3.2. Borehole Stability. The stability of the borehole determines whether the borehole can achieve an effective drainage. Since the borehole is designed to be a layered lower
slice, under the action of mining stress in the upper slice, it is easy to induce borehole collapse, resulting in drainage failure.

4.1.3.3. Borehole Length and Extraction Negative Pressure. At this stage, with the maturity of directional drilling technology, borehole construction can reach thousands of meters. However, the longer the borehole, the larger the gas inflow in the whole drainage length, and the faster the negative pressure decays from the orifice to the bottom of the hole. At the same time, the gas flow frictional resistance increases, the drainage failure is caused in the bottom area of the hole. Therefore, the effective extraction needs to match a reasonable borehole length and negative pressure, and a high-pressure extraction system is used in this area of the site, with a negative pressure of 40 kPa, which can satisfy the negative pressure distribution for the entire length of the borehole.

4.2. Gas Migration Law of the Lower Slice. Figure 12 is a schematic diagram of the gas flow in the lower slice after upper slice mining. Owing to the negative pressure extraction in the upper slice goaf, the lower slice stress reduces, and a large amount of gas emits into the goaf, which is prone to gas overlimit accidents at the working face. When long boreholes are arranged in the lower slice, the layer where the boreholes are located divides the lower slice into two parts, and the upper part pressure relief gas flow in the goaf and the borehole, as shown in Figure 12, migration mode 1. The lower part pressure relief gas is cut flow, as shown in Figure 12, migration mode 2.

4.3. Pressure Relief Gas Extraction and Cut Flow Technology. After the upper slice mined, it is easy to form a mining fracture in the lower slice, which is conducive to the flow of pressure relief gas. In order to cut off the gas flow into the goaf, the extraction and cut flow technology is proposed, where long boreholes are arranged along the strike of the lower slice. The technology is innovative. It solves gas emission and can reduce the gas content of the coal seam. Based on the gas migration law shown in Figure 12, the use of this technology needs to determine the drilling horizon, and the relationship is balanced between the gas flow volume into the goaf and the total extract volume, and the gas emission volume of goaf is ensured which cannot exceed the gas extraction capacity of the upper slice working face. At the same time, the gas extraction volume is ensured in the lower slice maximization. When the drilled layers close to the upper slice, it can reduce gas emission effectively and prevent the gas from exceeding the limit. However, for the lower slice, the extraction volume is small, which is not conducive to the gas prevention of lower slice mining. On the contrary, it is not conducive to the upper layer gas control. Therefore, a reasonable horizon needs to give consideration to gas control in the upper slice goaf and gas control in lower slice mining. It is necessary to predict the amount of gas emission into the goaf and the amount of extraction.

5. GAS MIGRATION LAW UNDER THE LOWER SLICE EXTRACTION

5.1. Geometric Model. According to the coupling model, Comsol Multiphysics software is used to solve the problem, gas extraction is simulated at different layers, and the extraction volume is obtained. In the lower slice extraction, due to the roof caving and compaction in the middle of the goaf, the pressure relief emission intensity is weaker than that of the lower slice, and a gas storage space is formed above the caving region in the middle. Gas emission in the middle part of the goaf has little impact on the working face. Therefore, the main problem is the gas emission of the “O” ring on the return airway, and it causes the upper corner gas to exceed the limit. In the actual arrangement, drilling holes are also concentrated on the return airway side. Since the “O”-ring area on the return airway side is narrow, assuming that the gas emission in this area is uniform, a plane model is selected for analysis. The gas emission ratio and the gas control ratio in the plane can be obtained to represent the emission law of the three-dimensional stope. Therefore, the plane model and selecting profile of the borehole trend are used to study. Among them, the gas content is 4.3 m³/t, and the gas pressure is 0.6 MPa. The borehole diameter is 150 mm, and the borehole length is 30 m. The negative pressure is 40 kPa, and the plane model is 30 m × 13 m. The relevant parameters of the model are shown in Table 5.

Table 5. Physical Parameters of the Tingnan Mine

| parameter name | unit |
|----------------|------|
| initial porosity φ₀ | 0.085 |
| kinematic coefficient of viscosity μ | 1.08 × 10⁻⁴ Pa s |
| apparent density ρ | 1.35 t/m³ |
| pore pressure p | 0.6 MPa |
| Langmuir adsorption constant a | 22 m³/t |
| Langmuir adsorption constant b | 0.9 MPa⁻¹ |
| negative pressure | 40 kPa |
| adsorption ambient temperature T | 303 K |
| elastic modulus K₀ | 2.56 × 10⁹ MPa |
| Poisson’s ratio ν | 0.12 |
| gas density ρg | 0.717 kg/m³ |
| initial permeability k₀ | 0.0194 mD |
| gas molar volume V_m | 22.4 × 10⁻³ m³/mol |

The simulation is divided into two situations: (1) the lower slice has no drilling for extraction; (2) the lower slice boreholes are located at the −3, −4, −5, −6, −7, and −9 m horizon. Figure 13 shows a part of the geometric model.

5.2. Numerical Simulation Boundary Conditions and Initial Conditions. Initial conditions: The initial gas pressure of the coal seam in the simulation area is 0.6 MPa, and the gas extraction pressure is 0.04 MPa. Boundary conditions: The upper boundary of the model is the “O” ring pressure relief area of the goaf according to the distribution law of stope inclination stress, and no loading is applied to the boundary. The boundary is atmospheric pressure 0.1 MPa. The lower boundary of the model is the lower slice coal seam floor, which is regarded as no flow. The left and right boundaries of the model are the original pore pressures except for the drilling position.

5.3. Results and Analysis. In the analysis of the simulation results, the time interval was selected as 60 days, and the total simulation time was 360 days. Taking 60 days as the time interval, the drainage duration that affects the difference of gas migration can be compared. At the same time, the total mining time of this working face is 360 days. When the drilling is officially designed after the experiment, the drilling length of the directional drilling rig can reach 800–1000 m. Selecting 360 days can ensure the analysis of the entire extraction phase.

5.3.1. Gas Migration Law in the Lower Slice without the Borehole. When there is no drilling for extraction, the pressure relief gas flows into the goaf from the lower slice. This can be seen from Figure 14 with the gas emission, and the gas pore
Figure 13. Model of the numerical calculation.

(a) Lower slice without borehole
(b) The lower slice borehole is 3m away from the goaf
(c) The lower slice borehole is 5m away from the goaf
(d) The lower slice borehole is 7m away from the goaf

Figure 14. Contour map of pressure without borehole extraction in the lower slice.
pressure in the lower slice decreases. The pressure relief range gradually develops downward. The closer to the lower, the closer the gas pressure is to the initial pressure value.

5.3.2. Gas Migration Law in the Lower Slice with Borehole Extraction in Different Layers. 5.3.2.1. Borehole is Located in the Lower Slice $-3 \text{ m}$ Horizon. When the extraction boreholes are arranged in the lower slice, the radial flow is simplified as a unidirectional flow by using a plane model. At this time, there is an interface between the gas flowing into the borehole and the gas flowing into the goaf, and the pore pressure maximum position is regarded between the borehole and the goaf as the interface. As Figure 15 shows that when the borehole is arranged at the $-3 \text{ m}$ horizon in the figure, drainage to 60 days, the pressure interface is between $-1$ and $-2 \text{ m}$ horizon of the lower slice. After drainage to 180 days, the interface moves up between the 0 and $-1 \text{ m}$ horizon of the lower slice.

5.3.2.2. Borehole is Located in the Lower Slice $-4 \text{ m}$ Horizon. As Figure 16 shows that when the borehole is arranged at the $-4 \text{ m}$ horizon in the figure, drainage to 60 days, the pressure interface is located $-2 \text{ m}$ horizon of the lower slice. After drainage to 240 days, the interface moves up between the $-1$ and $-2 \text{ m}$ horizon of the lower slice. After drainage to 300 days, the interface is between 0 and $-1 \text{ m}$ horizon of the lower slice.

5.3.2.3. Borehole is Located in the Lower Slice $-5 \text{ m}$ Horizon. As Figure 17 shows that when the borehole is arranged at the $-5 \text{ m}$ horizon in the figure, drainage to 60 days, the pressure interface is between $-2$ and $-3 \text{ m}$ horizon of the lower slice. During borehole extraction, the interface moves up, and at last, the interface is located $-2 \text{ m}$ horizon of the lower slice.

5.3.2.4. Borehole is Located in the Lower Slice $-6 \text{ m}$ Horizon. As Figure 18 shows that when the borehole is
arranged at the $-6$ m horizon in the figure, drainage to 60 days, the pressure interface is located $-3$ m horizon of the lower slice. After drainage to 360 days, the pressure interface is located slightly greater than $-3$ m horizon of the lower slice and is closer to the goaf. During borehole extraction, the interface moves up inapparently.

5.3.2.5. Borehole is Located in the Lower Slice $-7$ m Horizon. As Figure 19 shows that when the borehole is arranged at the $-7$ m horizon in the figure, drainage to 60 days, the pressure interface is between $-3$ and $-4$ m horizon of the lower slice. Drainage to 360 days, the interface moves up inapparently.

5.3.2.6. Borehole is Located in the Lower Slice $-9$ m Horizon. As Figure 20 shows that when the borehole is arranged at the $-9$ m horizon in the figure, drainage to 60 days, the pressure interface is between $-4$ and $-5$ m horizon of the lower slice. After drainage to 360 days, the interface moves up inapparently.

To sum up, when the boreholes are arranged in different horizons, the initial interface is approximately located in the middle between the borehole horizon and the 0 m horizon in the figure. With the extraction time increasing, the interface moves up. Also, when the borehole horizon is closer to the 0 m horizon, the extraction time, which causes interface to move up, is shorter. When the borehole horizon moves farther to the 0 m horizon, with the extraction time increasing, the interface tends to remain unchanged. The borehole horizon is located at $-6$, $-7$ and $-9$ m, and the interface hardly moves. This variation rule corresponds to the permeability distribution rule of the floor.

Based on the above numerical simulations, unit a thickness model is selected for analysis, it can obtain the drilling volume of the lower slice of a different horizon, the goaf emission volume during the extraction and cut flow stage, and the total reduction of coal seam gas. In the calculation, the thickness of the model is considered to be 1 m; that is, the size of the analysis model is $30 \times 13 \times 1$ m, as shown in Figures 21–23.

As shown in Figure 21, the extraction volumes at different horizons increase with extraction time. After drainage to 60 days, when the borehole is located at the $-3$ to $-9$ m horizon in the lower slice, the extraction volume is basically the same.
With the increase in the extraction time, for the same extraction days, the extraction volume of boreholes in the layers of −3 to −7 m gradually increases, and the increased volume gradually decreases, and among them, the drainage volume at the −6 m layer is relatively close to that at the −7 m layer. Boreholes are further close to the lower slice floor, and when the boreholes are located in −9 m, during the 0−180 day extraction period, the extraction volume is the same as that of −7 m. When the number of days for extraction reaches 210 days, the −9 m extraction volume is slightly less than −7 m. By comparing the abovementioned pressure contours line, it can be seen that when the horizon changes from −3 to −7 m, the borehole gradually moves away from the goaf, and the extraction volume above the borehole gradually increases. At the same time, it can be seen from the pressure contour line below the hole that when the −6 m horizon is drained for 300 days, the pressure contour line is in contact with the lower boundary, and the boreholes at the −3 to −6 m horizon can fully extract the lower slice during the whole extraction stage. The drainage volume above the hole is increased, and the drainage volume below the hole is fully extracted, so the drainage volume at the −3 to −6 m layer gradually increases.

When it is located at the −7 m layer, the pressure contour line touches the lower boundary after 180 days, but the drainage volume above the hole further increases, resulting in an increase in the drainage volume after 180 days of drainage compared with the −6 m horizons. When it is located at the −9 m layer, the extraction pressure contour above the hole is close to −7 m during the entire extraction stage, but because it is closer to the lower slice floor, after 180 days of drainage, the pressure contour line below the hole changed significantly compared with −7 m, and the extraction volume decreases, so the total extraction volume begins to decrease after 210 days of extraction. The −12 m horizon is similar to −9 m; therefore, the simulation will not be carried out.

When the final extraction reaches 360 days, the extraction volume of the borehole at the −7 m horizon reaches the maximum. This result shows that the farther the boreholes are arranged from the 0 m horizon, the larger the amount of gas extraction volume is, but the increasing trend gradually weakened. There is a layer with the largest extraction volume, and the extraction volume begins to decrease below this layer.

Figure 22 shows that the gas emission in the goaf increases with the extraction time, when the borehole is in different

![Figure 17. Contour map of pressure when the borehole is localized at −5 m horizon.](https://doi.org/10.1021/acsomega.2c02255)
The data in the figure shows that, with an increase in the extraction time, the closer the borehole is to the 0 m horizon, the smaller the gas emission is in the goaf. When the drilling hole is located at the −9 m horizon, the gas emission in the goaf is close to that without borehole. In the early stage of extraction, the closer the borehole is to the 0 m horizons, the shorter the time is to cut the flow. For example, for the −3 m horizons after 60 days of extraction, the gas emission volume is lower than that without drilling. For the −7 m horizons, after 120 days of extraction, the gas emission volume is lower than that without drilling. For the −9 m horizons, after 150 days of extraction, the gas emission volume is lower than that without drilling. The pressure contour lines reflect the same pattern.

Figure 23 shows that the gas reduction volume with emission in the goaf is the difference between the gas emission volume in the goaf when there is no borehole and the gas emission volume in the goaf after extraction. The results show that the closer the borehole horizon is to 0 m, the greater the amount of gas reduction quantity. When the borehole is arranged at −9 m, the cut flow volume with emission in the goaf is close to 0.

In order to obtain the influence of boreholes extraction on gas prevention and treatment, the goaf emission volume after arranging the boreholes and the goaf emission volume without drilling holes are compared, and the calculation results are shown in Table 6.

It can be seen from Table 6 that when the borehole is located at the −3 m horizon, the goaf emission volume can be reduced to 51.25% of the emission volume without drilling and with the increase in horizon, the emission volume reduction ratio decreases. When the drill hole is arranged at the −9 m horizon, the goaf emission volume is reduced to 98.29% of the emission volume without drilling. The above data also shows that at different horizons, the required time to limit the gas emission in the goaf is different. When the borehole is located at the −3 m horizon, the gas emission in the gob can be controlled for 60 days. When the borehole is located at the −9 m horizon, it needs 150 days.

**Figure 18.** Contour map of pressure when the borehole is localized at −6 m horizon.
To sum up, for the selection of the lower slice borehole horizon, it is necessary to consider the final extraction volume and the impact on the gas emission in the goaf. When the horizon is close from the goaf, the control effect of gas emission in goaf is obvious, and it takes a short time to solve the problem, but it is not conducive to the prevention and control of gas during lower slice mining. When the layer is far away from the goaf, the extraction volume increases, but the cut flow effect is not obvious. When the borehole's horizon is too close to the lower slice bottom, it is not only unfavorable for the cut flow but also leads to the reduction in the drainage volume. When the boreholes are located at the \(-7\) m horizon, the extraction volume reaches the maximum. Therefore, the boreholes arrangement range is between \(-3\) and \(-7\) m horizons.

5.4. Field Verification. According to the engineering background, the extraction data of different horizons is shown in Figures 24–27. The 1# hole is located at \(-3\) m horizon of the lower slice. After the working face is pushed through the hole, the mixing extraction volume in the hole increases, indicating that the permeability of the coal seam increases after pressure relief, and the corresponding drainage concentration is lower than that of the 2# and 3# holes. It may be due to the connection of this area to the goaf, causing some air to flood into the borehole. When the borehole is located 10–20 m behind the working face, the mixing extraction volume decreases, and the preliminary analysis is that the boreholes are damaged and partially blocked under the influence of upper slice mining. Therefore, the borehole’s stability should be further considered in the borehole arrangement. 17

2# and 3# boreholes keep maintaining a high mixing volume and concentration during the extraction process, and the gas extraction volume of this horizon increases, which has an obvious effect on pressure relief gas extraction. The 4#
Figure 20. Contour map of pressure when the borehole is localized at −9 m horizon.

Figure 21. Borehole extraction volume in different horizons.

Figure 22. Gas emission volume under different horizons of borehole extraction.
borehole is located at the 12 m horizon of the lower slice, and the corresponding extraction mixing volume and concentration are relatively low, similar to the preextraction borehole drainage, which has no obvious effect on pressure relief gas extraction.

The field measurement shows that with the increase in the distance between the borehole horizon and the goaf, the effect of pressure relief gas extraction is weakened.

5.5. Drilling Horizon Determination. According to the theory of rock formation plastic slip, the failure depth of the lower slice is solved when the upper slice is mined.

\[
h_0 = \frac{x_0 \cos \phi_0}{2 \cos \left( \frac{\pi}{4} + \frac{\phi_0}{2} \right) \tan \phi_0}
\]  

(12)

where \(h_0\) is the maximum failure depth of the lower slice, m; \(x_0\) is the breaking length for the front end of the working face, m; \(\phi_0\) is the average friction angle of the lower slice coal seam, °.

It can be seen from Figure 5 that when the working face is advanced to 70 m, the stress value of the toward the stress monitoring point at 75 m reaches the maximum value. After the working face is excavated for 10 m, the working face is pushed past the measuring point, and the stress at the measuring point decreases rapidly. The excavation step distance is large, and the detailed change rules of the working face close to the toward measuring point have not been monitored, but it can be determined that \(x_0 \leq 5\) m. Taking \(x_0 = 5\) m, \(\phi_0 = 20°\) (According to Table 1) and bringing it into formula 12, it can get \(h_0\) to be 5.80 m, that is, the failure depth is 5.80 m.

Based on the field measurement results and the gas migration law obtained by numerical simulation, the borehole layout is determined as the lower slice −6 m horizon, which can not only ensure the adequate extraction of pressure relief gas but also avoid induction air. The borehole in this horizon is not damaged and can also cut flow 10% of the gas that emission into the goaf.

6. DISCUSSION

The above research process focuses on the gas migration law when determining the horizon, and the stability of the borehole horizon.

![Figure 23. Gas emission reduction volume under different horizons of borehole extraction.](https://pubs.acs.org/journal/acsodf)

Table 6. Comparison of the Emission under Different Horizons of Borehole Extraction

| Time (d) | borehole horizon | gas emission volume (m³) | percentage of cut flow gas volume % |
|----------|------------------|--------------------------|-----------------------------------|
| 30       | borehole horizon -3 m | 204.56                 | 100                                |
| 60       | borehole horizon -4 m | 204.56                 | 100                                |
| 90       | borehole horizon -5 m | 204.56                 | 100                                |
| 120      | borehole horizon -6 m | 204.56                 | 100                                |
| 150      | borehole horizon -7 m | 204.56                 | 100                                |
| 180      | borehole horizon -8 m | 204.56                 | 100                                |
| 210      | borehole horizon -9 m | 204.56                 | 100                                |

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borehole is also considered in the whole design. Reference 17 carried out the numerical simulation and theoretical analysis to study the relationship between the borehole stability and the loading rate, and the actual borehole stability is not only related to the failure depth of the bottom plate but also to the carrying load, that is, the drilling in the undamaged area of the bottom plate may still be damaged under a large load. It will be further supplemented in the follow-up research.

At the same time, this study only analyzes the cut flow effect in the vertical direction and proposes the borehole horizon. The engineering background is the “O” ring area corresponding to the upper corner, which is easy to form supports due to insufficient caving during the mining process. The corresponding compaction stress is small, and the permeability is large. The emission gas can flow into the working face through this channel. For slice mining projects, in addition to the gas channel easily formed in the upper corner area, there is some gas that flows into the working face in the uncompacted area behind the goaf and accumulates in the upper corner with the leakage of air flow. The above situation requires the establishment of a 3D model. The stress recovery state and permeability distribution of the goaf need to be fully considered, and further research will be carried out in the future.

7. CONCLUSIONS

1 Based on the experiment of the permeability evolution law under the mining stress. The relationship is established between permeability and mining stress and pore pressure, and the permeability distribution law of the lower slice pressure relief coal seam is obtained under the extra-thick coal seam slice mining.

2 The extraction and cut flow technology of the lower slice long boreholes is proposed under slice mining. Arrangement of the drainage holes in the lower slice can extract pressure and relieve gas, and the drainage rate of lower slice is improved. At the same time, it can prevent pressure gas emission into the goaf, reducing the pressure of gas prevention and controlling the upper slice mining. The reasonable horizon design of the lower slice...
slice boreholes needs to comprehensively consider the gas control of the upper slice goaf and the lower slice coal seam, and it is necessary to predict the gas emission into the goaf and the extraction amount under the condition of drainage.

3 The fluid-solid coupling model of gas seepage is established in the lower slice pressure relief coal seam, and the gas migration law of pressure relief coal seam is obtained when drilling in different horizons. At the horizons of −3, −4, −5, −6, −7, and −9 m, the corresponding gas volume emission in the goaf is reduced to 51.25, 66.69, 81.18, 90.55, 95.31, and 98.29% of that without boreholes, respectively. Also, the corresponding gas emission volume is 344.7, 448.4, 545.9, 608.9, 640.9, and 660.9 m$^3$. The corresponding gas extraction volume is 1143.4, 1269.1, 1358.5, 1423.5, 1461.1, and 1440.2 m$^3$.

4 The field industrial test was carried out, and the actual measurement showed that when the borehole is located at the −6 and −9 m horizons of the lower slice, the drainage concentration and mixing volume are higher, and the drainage effect of the pressure relief gas is better. When they are located in the lower slice −3 m horizon, the boreholes are easy to be damaged by the mining effect. When it is located in the lower slice −12 m horizon, the effect of pressure relief gas drainage in the lower slice is reduced. Considering the effect of the pressure relief gas drainage in the lower slice, the amount of gas emission in the goaf, and the boreholes stability, the final horizon is determined to be −6 m.

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Notes

The authors declare no competing financial interest.

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