Study on the gas migration laws of non-pillar mining with gob-side entry retaining in high gas outburst coal seam

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Abstract. Mining fractures are the channel of gas migration, and it is important to figure out the gas migration laws for gas control. Combined with the actual geological conditions of Shaqu No. 2 coal mine, a numerical model of no-pillar mining with automatically retained entry was built to simulate the deformation and fracture of overburden rock and the evolution laws of cracks above the goaf during mining. Subsequently, CFD software is used to theoretically stimulate the gas concentration distribution laws of non-pillar mining with the automatically retained entry in the stope under non-drainage and high-level borehole drainage conditions. The laws of gas concentration in the stope were compared and analyzed under the condition of the Y-type ventilation of non-pillar mining and U-type ventilation of coal pillar mining. The results show that Y-type ventilation of non-pillar mining reduces the gas concentration in the upper corner of the working face and the goaf, and effectively solves the gas accumulation problem in the upper corner of the working face in the mode of U-type ventilation of coal pillar mining. On this basis, the high-level borehole drainage technology is adopted to effectively reduce the gas concentration in the goaf. The research has certain guiding significance for the gas management of non-pillar mining with gob-side entry automatically retained.

1. Introduction
At the beginning of the 21st century, with the continuous reduction of coal resources, the problems of low recovery rate and a serious waste of resources caused by coal pillar mining have become increasingly prominent. Leaving coal pillars between the working faces will not only cause a great waste of resources, but also easily cause geological disasters such as rock bursts, open fires, and gas accumulation [1-2]. Gas disasters are a common geological disaster, and gas explosion not only causes a large number of casualties, but also destroys shaft
facilities, interrupts production, and easily causes secondary disasters such as coal dust explosions and mine fires [3-4]. To improve the recovery rate of coal resources and solve the dynamic disasters of coal mines, Chinese scholars proposed the technology of non-pillar mining with automatically retained entry [5-8]. Before the coal seam of the working face is mined, the directional blasting technology is used to pre-crack and cut the roof at the edge of the mining roadway. After the working face is mined, under the action of the mine pressure, the roof will automatically form a roadside along the pre-cracked and cut seam, thereby retaining the original roadway. Realize pillarless mining [9-11].

Because coal pillar mining has always been the main method in coal mine production in China, the research on the law of gas migration in working faces and goaves is also based on this mining system. Li Ying-ming conducted a numerical simulation and comparative study on the gas distribution law in the goaf under the conditions of drainage with and without buried pipes in U-type ventilation working face [12]; Wu Xiao-min used FLUENT software to compare the U-shaped and U-shaped Numerical simulation of the flow field in the goaf under U+L type ventilation mode was carried out, and the gas concentration distribution in the goaf and the distribution of spontaneous combustion danger zone in the goaf under the two ventilation modes were compared and analyzed [13]; Gao Gui-xiang analyzed and studied the U+L type ventilation method is the method of controlling the gas accumulation in the upper corner, which solves the problem of easy accumulation of gas in the upper corner [14]; Zhang Dong analyzed and studied the composition, characteristics, key technologies and treatment effects of the "double U" ventilation method, and practice shows that the "double U" type ventilation method has strong gas processing capacity, which can eliminate the problem of gas accumulation in the upper corner and ensure safe production of the working face [15]; Zhu Jian-fang comparatively analyzed the advantages and disadvantages of the "U+L" and "W" ventilation methods, showing that the "W" ventilation method has wider applicability [16].

After recent years of testing and promotion, a large number of research results have been achieved in the technology of non-pillar mining with automatically retained entry, but the main research is concentrated on key technical parameter design, overlying rock movement and underground pressure law, roadway stability control [17-19], and there is little research on the law of gas migration in the application of this technology. The clarification of the gas migration law in the goaf is of great significance to the upper corner gas control and fire prevention in the goaf [20-21]. Therefore, this paper uses the CFD software FLUENT, based on the "Y" type ventilation of self-made roadway without coal pillar, and combined with the mining situation of No.3402 working face in Shaqu No.2 coal mine, comprehensively studies the gas migration law in goaf during the mining process.

1. "Y" type ventilation system for non-pillar mining with automatically retained entry
The test working face is 3402 working face of Huajin Coking Coal Shaqu No. 2 Mine, and the coal seam is 3# coal. The thickness of the coal seam is 0.82~0.95m, the average thickness is 0.87m, and the average inclination angle of the coal seam is 4°. The working face buried depth is 380~450m, the strike length of the working face is 839.4m, and the dip length is 200m, and the designed roadway length is 600m. The test roadway is 3402 belt roadway, the roadway section is rectangular, the roadway clear height is 2.5m, and the clear width is 4m. The immediate roof of the coal seam is fine-grained sandstone, the main roof is
medium-grained sandstone, and the immediate bottom is medium-grained sandstone. The column diagram of drilling holes near the working face is shown in Figure 1.

| Lithology          | Thickness /m | Histogram |
|--------------------|--------------|-----------|
| Medium-grained sandstone | 6.20         |           |
| 2#coal             | 0.40         |           |
| Siltstone          | 3.27         |           |
| Fine-grained sandstone | 3.48     |           |
| 3#coal             | 0.87         |           |
| Medium-grained sandstone | 2.10   |           |
| Sandy mudstone     | 3.60         |           |
| Fine-grained sandstone | 6.90   |           |

**Figure 1.** Drilling histogram

The principle of the non-pillar mining with automatically retained entry technology is to use constant resistance and large deformation anchor cables to strengthen and support the roof of the reserved roadway after the reserved roadway working face system is formed. Before the mining of the working face, the bilateral cumulative tensile blasting technology is used to pre-split blast the roof of the roadway along the direction of the gob along the goaf side to form a slit structure surface, cutting off the stress transmission path of the roof of the goaf and the roadway roof. After the working face is mined, the roof of the goaf gradually collapses along the cutting face under the influence of self-weight and mine pressure. When the working face is ventilated, the left roadway is used as the return airway, and the air return system is composed of the air inlet of the double crossheading of the working face, forming a Y-shaped ventilation system with "two inlets and one return" at the working face [22]. The Y-type ventilation system of 3402 working face in Shaqu No.2 coal mine is shown in Fig.2.

**Figure 2.** Y-type ventilation system of mining with no pillar mining with automatically formed entry
2. Numerical simulation of overlying rock failure in goaf of non-pillar mining with automatically retained entry

2.1 Establishment of the numerical model

Based on considering the actual engineering conditions and simplified calculations, aiming at the production geological conditions of the belt roadway in the 3402 working face of Shaqu No. 2 Mine, the FLAC3D numerical simulation software was used to establish a numerical model. The Mohr-Coulomb model was selected for this model. The size of the model is: length×width×height=300m×300m×60m. The size of simulated roadway excavation is: 4m×2.5m, and the size of working face excavation is: 200m×200m×2.5m. The roadway is buried at a depth of 400m and is driven along the roof of the coal seam.

The left and right boundaries of the model limit the x-direction displacement, the front and back boundaries limit the y-direction displacement, and apply the horizontal compressive stress varying with the depth; the lower boundary limits the z-direction displacement; the upper boundary applies the uniform self-weight stress. The specific rock mechanical parameters of the model are shown in Table 1.

Table 1. Strata mechanical parameters of the numerical model

| Rock formation     | Layer thickness /m | Bulk modulus/ GPa | Shear modulus/ GPa | The angle of internal friction/° | Tensile strength /MPa | Density /(kg/m³) | Group cohesiveness/s/MPa |
|--------------------|--------------------|-------------------|--------------------|-------------------------------|-----------------------|------------------|------------------------|
| Medium-grained sandstone | 6.20 | 18.46 | 8.52 | 47.4 | 1.12 | 2730 | 5.44 |
| 2#coal siltstone   | 0.40 | 1.14  | 0.59 | 28   | 0.9  | 1430 | 2 |
| Fine-grained sandstone | 3.27 | 5.0   | 5.45 | 43.1 | 0.38 | 2670 | 7.75 |
| 3#coal Medium-grained sandstone | 3.48 | 22.13 | 20.96 | 45.4 | 2.85 | 2790 | 6.86 |
| Sandy mudstone     | 0.87 | 1.14  | 0.59 | 28   | 0.9  | 1430 | 2 |

2.2 Analysis of the failure of the overlying strata in goaf

To study the deformation and failure of the overlying strata and the evolution of cracks at different distances of the working face, this simulation is divided into 5 excavations, each excavation 40m. In the middle of the goaf, slices are made along the direction of the coal seam, and the deformation and failure state of the overlying rock strata affected by mining is shown in Figure 3.

When the excavation size is 40m, due to the short excavation distance, the overlying rock layer is not damaged in a large area, and only the rock layer about 10m above the roof undergoes plastic failure under the influence of mining. With the continuous advancement of the working face, the roof of the goaf above the working face will further collapse and deform,
and the deformation and destruction will increase, especially when the excavation size is 200m, the overlying rock formation is most severely damaged, the longitudinal extension of plastic zone is "saddle" shape and tends to be stable, and the depth of plastic failure of roof is about 27m, among them, the rock formation within 5m above the coal seam has tensile and shear failure, which can be considered as a caving zone; the overlying rock within 5m~27m above the coal seam enters the tensile failure zone, which can be considered as a fracture zone [23].

![Figure 3. Cloud map of the plastic area of overlying rock with different excavation footage](image)

### 3. Numerical simulation analysis of gas migration in non-pillar mining with automatically retained entry

#### 3.1 Seepage control equation in goaf

Generally, the goaf is regarded as a porous medium composed of the coal-rock mixture, and the gas and air mixture in the entire calculation domain is regarded as an incompressible ideal
gas. The flow field can be applied to the porous medium model, and the calculation follows the mass equation and momentum equation, and energy equation [24].

(1) Mass conservation equation of the flow field in the goaf

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial X_i} = S_m
\]  

(1)

Where: \(t\) is the time, \(s\); \(\rho\) is the gas density, \(kg/m^3\); \(u_i\) is the velocity component in \(i\) direction, \(m/s\); \(S_m\) is the mass source term, \(kg/(m^3s)\).

(2) The momentum conservation equation of the flow field in the goaf:

\[
\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial X_j} = -\frac{\partial p}{\partial X_i} + \frac{\partial \tau_{ij}}{\partial X_j} + \rho g + F_i + S_i
\]  

(2)

Where: \(k\) is the heat transfer coefficient of the fluid; \(\tau\) is the viscous dissipation term; \(F_i\) is the gravity and external volume force, \(N\); \(S_i\) is the momentum source term, \(N\).

(3) The energy conservation equation of the flow field in the goaf

\[
\frac{\partial (\rho t)}{\partial t} + \text{div}(\rho ut) = \text{div}\left(\frac{k}{C_p} \text{grad}(T)\right) + S_e
\]  

(3)

Where: \(k\) is the time; \(\tau\) is the gas density, \(N/m^2\); \(C_p\) is the specific heat capacity of the object; \(S_e\) is the mass source term, \(N\).

3.2 Porosity and permeability equation of goaf

The porosity of the caving zone in the goaf is distributed in a "shovel shape", that is, the porosity in the shallow part and the sides of two roadways is large, while that in the middle and inside is small. The distribution of porosity satisfies the following equation [25]:

\[
\phi(x, y) = 1 + \frac{h_y}{h_y + H - [h_y + K_{\rho_0} - 1][1 - e^{-\frac{L}{2}}]} - 1
\]  

\[
\phi(x, y) = 1 + \sigma_0^{-1} \beta \left(\frac{L}{2} - y\right) \sin \alpha
\]  

(4)

Where: \(\phi\) is the porosity distribution; \(K_{\rho_0}\) is the residual breaking expansion coefficient of the broken rock mass of the immediate roof; \(L\) is the length of the basic broken rock block, \(m\); \(L_y\) is the inclined length of the goaf, \(m\); \(h_y\) is the thickness of the direct roof, \(m\); \(H\) is the mining height of the working face, \(m\); \(\sigma_0^{-1} \beta\), all take 1.

According to the Blake-Kozeny formula [26], the permeability of porous media is:

\[
\epsilon = \frac{D_a^2}{150} \frac{n^3}{(1-n)^2}
\]  

(5)

Where: \(D_a\) is the average particle size of the porous media framework, \(m\); \(n\) is the porosity.

According to the field test data and CFD simulation experience, the porosity and permeability distribution in different areas of the caving zone and fracture zone in the porous media model of the goaf are determined through repeated simulation tests.
3.3 Model establishment and boundary conditions

To study the law of gas concentration migration in the working face and the goaf under the technical conditions of non-pillar mining with automatically retained entry, and to guide the gas control in the goaf, the model was established based on the simulation results of "upper two zones" and geological conditions of 3402 working face in Shaqu No.2 coal mine, and use FLUENT software for numerical simulation. The basic situation of the working face and the setting of solution boundary conditions are shown in Table 2.

The setting of porosity, oxygen consumption rate, viscous resistance coefficient, and inertial resistance coefficient in the goaf is completed by compiling UDF, which makes it closer to the actual situation of the goaf.

Table 2. The parameters of model and CFD conditions

| Serial number | Parameter name          | Parameter value                                      |
|---------------|-------------------------|------------------------------------------------------|
| 1             | Working face size       | 6 m×200 m×2.5 m                                      |
|               |                         | Intake airway: 20 m×4 m×2.5 m                        |
| 2             | Roadway size            | Air distribution airway: 20 m×4 m×2.5 m             |
|               |                         | Ventilation roadway: 20 m×4 m×2.5 m                 |
| 3             | Goaf-caving zone size   | 300 m×200 m×5 m                                     |
| 4             | Goaf-fissure zone size  | 300 m×200 m×22 m                                    |
| 5             | Gas composition in goaf | Ventilation roadway :100%CH₄                           |
| 6             | Absolute gas emission rate | 12 m³/min                      |
| 7             | Intake airway speed     | Ventilation roadway: 1.33 m/s                        |
|               |                         | Ventilation roadway: 0.75 m/s                       |
| 8             | Gas composition of intake airway | 21%O₂, 79%N₂                     |

Figure 4. Geometric model of the goaf in Y-type working face

3.4 Gas distribution law of non-pillar mining with automatically retained entry without drainage

3.4.1 Distribution law of gas in the stope

When the goaf of 3402 working face is not drilled on the ground, the gas concentration distribution law is shown in Figure 5. In the Y-type ventilation mode, the gas concentration in the upper corner of the working surface is small. Extending to the deep part of the goaf, the gas concentration gradually increases, causing a large amount of high-concentration gas to collect in the deep part of the goaf. This is due to the gradual compaction of the rock layers in the deep part of the goaf, and the porosity is much lower than that in the shallow part, and air cannot penetrate, forming a "gas warehouse". When the roof collapses, the large amount of gas accumulated in the goaf will quickly gush out from the fissure zone and other positions to
the working face under the impact of the incoming pressure. This part of the gas is under the action of the wind from the two roadways. It will rush to the non-pillar mining with automatically retained entry, avoiding the accumulation of gas on the working face and upper corners, causing the problem of excessive concentration.

![Diagram](image)

**Figure 5.** Distribution laws of gas concentration under no-pillar mining with automatically retained entry

3.4.2 Flowfield distribution law in strike goaf

Take $X=40m$, $X=70m$, $X=100m$ slice cloud images to analyze the distribution law of gas concentration along $X$ (that is, the direction of the working face), as shown in Figure 6. It can be seen from Figure 6 that at the same height, the greater the proportion of the "red" area toward the depths of the goaf, the greater the gas concentration toward the depths of the goaf. Also, because the gas density is 0.554 times the air density [27], the gas in the goaf is accumulated in the direction of the roof under the action of buoyancy, resulting in a higher gas concentration along the coal roof.

![Diagram](image)

**Figure 6.** Flowfield distribution law in strike goaf

(a) Gas distribution cloud map at $X=40m$
3.4.3 Distribution law of flow field in inclined goaf

Draw the reference line at X=60m and X=90m in the cloud chart to generate the concentration curve of gas with the trend, as shown in Figure 7. The trend of the curve shows that along the working face, from the side of the air inlet lane to the side of the air return lane, the gas concentration gradually increases, and the gas concentration growth trend gradually becomes gentle. The gas concentration near the inlet lane is smaller.

Fig. 6 Cloud map of the goaf towards gas distribution
3.5 The law of gas distribution in the stope of high-position borehole drainage of non-pillar mining with automatically retained entry

Based on the numerical simulation modeling of the undrained Y-shaped ventilation gas, keeping the basic physical parameters unchanged, and combining with the actual situation on the site, it is determined that the simulated high-level drilling holes in the goaf are a group of 5 groups, and the end of the drilling arranged in the fracture zone, the horizontal distance controlled by the end of each group of boreholes is 75m, 125m, 175m, 210m, 260m from the cut-hole, and the borehole diameter is 0.153m. Among them, the drainage flow of each group of boreholes is set according to the actual situation of the 3402 working face, which is achieved by setting a flow outlet in FLUENT. The drainage flow of each group of boreholes is set in fluent, and the pumping simulation results are shown in Figure 8.
It can be seen from Figure 8 that when high-level drilling is used to drain gas in the goaf, the drainage effect is better. The gas concentration on the side of the goaf near the non-pillar mining with automatically retained entry is significantly reduced, and the area of low-concentration gas is increased compared with the time when the gas is not extracted so that the gas concentration in the goaf area with air leakage into the non-pillar mining with automatically retained entry is also significantly reduced, and the gas concentration of the non-pillar mining with automatically retained entry and the return airway is reduced.

The drainage of the high-level borehole also intercepts part of the gas flow from the goaf to the working face, which makes the gas concentration near the working face gradually decrease. Besides, from the overall situation of the three-dimensional gas concentration distribution map of the goaf, the high concentration gas area inside the goaf is also significantly reduced. Therefore, the drainage method has a better effect on gas drainage control in the goaf and effectively solves the problems of excessive gas in the return airway and high concentration of gas in the deep part of the goaf.

4. Discussions

Figure 9 shows the distribution of gas concentration in the goaf under different mining and ventilation methods. It can be seen that the traditional coal pillar mining face adopts U-type ventilation system, because most of the gas in the goaf gushes to the upper corner of the working face and the return airway along with the air leakage, resulting in the gas accumulation in the upper corner of the working face and the gas concentration in the return airway exceeding the limit, which brings great safety risks to the production of the working face. However, under the Y-type ventilation method of non-pillar mining with automatically retained entry, only a small part of the gas in the goaf flows to the upper corners of the working face, which makes the gas concentration in the upper corner of the working face extremely low, which fundamentally solves the problem of gas accumulation in the upper corner of the working face and gas overrun in the return airway under the U-type ventilation mode.
Compared with Y-type ventilation, the curve of gas concentration growth under U-type ventilation is "steeper", and the curve on the side of the return airway is more obvious. The gas concentration near the corner of the working surface reaches more than 40%. The Y-type ventilation is 40m away from the upper corner of the working surface, and the gas concentration is still below 20%, which also shows that the Y-type ventilation can well solve the problem of high gas concentration at the upper corner of the working surface.

5. Conclusions
1) FLAC3D numerical software was used to simulate the deformation, failure, and fracture evolution law of overlying strata in the mining process of non-pillar mining with automatically retained entry at working face 3402 of Shaqu No. 2 mine. Finally, the caving zone height of overlying strata failure was determined to be 5m and the fracture zone height to be 22m, providing a foundation for the study of gas migration law.
2) Use FLUENT software to establish the Y-shaped ventilation working face of non-pillar mining with automatically retained entry, and the distribution of the gas concentration on the y-type ventilation face and goaf was obtained through simulation, that is, the gas concentration in the upper corner of the working face is small and extends to the deep part of the goaf, and the gas concentration increases gradually. In the vertical direction, due to the influx of pressure relief gas from the overlying coal seam and the gas accumulation in the goaf area toward the roof under the action of buoyancy, the gas concentration is the highest here.

3) The simulation of gas drainage by high-level borehole under the condition of Y-type ventilation in non-pillar mining with automatically retained entry is carried out. The results show that the combination of Y-type ventilation system and high-level borehole drainage and relief gas is of great significance to reduce the gas volume fraction in goaf and ensure safe production. Compared with the traditional U-type ventilation for mining with coal pillars, when the Y-type ventilation of non-pillar mining with automatically retained entry is adopted, most of the gas in the goaf is carried by the air leakage from the working face to the goaf and discharged into the non-pillar mining with automatically retained entry, and a very small part of the gas rushes to the upper corner of the working surface, which makes the gas concentration in the upper corner of the working surface extremely low, which fundamentally solves the problems of gas accumulation in the upper corner of the working surface and excessive gas in the return airway under the U-type ventilation mode.

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