Evolution and application of airflow permeability characteristics of gob in roof cutting and pressure releasing mining method

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INTRODUCTION
Since the industrial revolution, development of the economy, society, and energy industry has relied on fossil fuels such as coal, oil, and natural gas.1 Coal is the world's most widely distributed fossil fuel and currently accounts for more than 40% of global power generation.2,3 As a developing country, coal is the main energy source in China.4,6 Although China’s coal output is the highest in the world, as a nonrenewable resource, coal is limited. In addition, China's coal industry is under severe stress. There is an urgent need to control the energy cost, adopt advanced energy-saving equipment and technology, realize cost reduction and efficiency increase, and improve the economic...
benefits of the industry. Therefore, extracting limited coal resources by using scientific and rational production processes to provide energy security for economic growth in China and other developing countries is a significant research topic.\textsuperscript{7,8}

The traditional longwall working face layout uses one mining face to excavate two roadways, while simultaneously reserving a coal pillar (tens of meters wide) to balance the pressure transmitted from the roof of the upper mining face.\textsuperscript{9,10} However, the retained coal pillars have a low recovery rate and some cannot be recycled, resulting in significant resource loss. This loss can reach 40\% of the mine's recoverable reserves and is the root cause of coal mining losses.\textsuperscript{11,12} After years of research and exploration, by using the theory of “roof cutting shortwall beam”,\textsuperscript{13,14} Academician Manchao proposed the innovative technology of gob-side entry retaining formed by roof cutting and pressure releasing.\textsuperscript{15,16} With this method, only one roadway needs to be excavated in a mining face, and there is no coal pillar left between the working faces. Additionally, it has many advantages such as optimizing the stress of surrounding rock, eliminating the need for coal pillars, and reducing the extent of roadway excavation.\textsuperscript{17,18}

After adopting the roof cutting and pressure releasing mining method in place of the traditional long-wall mining method, the ventilation system of the mining face is adjusted from a “U”-type system to a “Y”-type system. Due to the large pressure on the wall of the roadway, the deformation of the wall is more serious, and it is difficult to block the gob and the roadway effectively. Moreover, because the roadway is on the return air side, there is an air pressure difference in the gob that causes the gas in the gob to escape from the side of the roadway and causes fresh airflow from the working face to continuously enter the gob. This changes the flow field of the working face, which widens the width of the oxidation temperature rise band and increases the risk of spontaneous combustion in the gob. Comparatively, in a “Y” ventilation system with a backfilling technology retaining roadway, the roadway wall is composed of a flexible membrane and high water material, and the roadway wall of the roof-cutting and pressure-relieving retaining roadway is composed of rock or coal fragments from the roof. The forming technology of the two is different, and the composition of the materials is also very different. Moreover, the filling technology and the cutting roof and release pressure technology have different stress transfer modes on the roof of the coal seam, which results in a large difference in the internal permeability of the gob and the influence on the wind flow migration of the working face. How the internal permeability of the gob formed by the roof cutting and pressure releasing technology has not been studied in depth. And the differences between the resulting airflow migration characteristics and the traditional “U”-type ventilation working face and the “Y”-type ventilation working face with a backfilling technology retaining roadway are also lacking in-depth research.

Based on the above analysis, the evolution of the permeability in the gob in roof cutting and pressure releasing mining method and the characteristics of airflow migration caused by the method were studied. A voidage evolution model and a permeability evolution model of the gob were constructed by the collapse characteristics of the gob with this method. Then, the fluent software was used to analyze the characteristics of airflow and the air leakage in the gob. This is necessary to prevent natural fires in the gob more effectively, hence, ensuring the safety of this method. Furthermore, it is of great significance to the development and promotion of the cutting roof and release pressure without coal pillar mining technology, and to the economic benefit of the coal industry.

2 | PRINCIPLE OF THE CUTTING ROOF AND RELEASE PRESSURE MINING TECHNOLOGY

The cutting roof and release pressure technology was proposed by Academician He Manchao in 2008.\textsuperscript{19} The working principle of the technology is as follows: When the working face is recovered, the inner surface and the side of the gob are supported by the constant-resistance and large-deformation anchor cable, and the working face is advanced by a certain distance. Along the direction of the trough, the directional blasting technology\textsuperscript{20} can precrack the roof forming a slit surface along the gob side of the retaining roadway. After mining, the dense single pillars are arranged close to the precracked line to support the roadside. The roof of the gob is automatically degraded along the slit surface due to its self-weight and mine pressure,\textsuperscript{21} thus retaining a slot in the working surface which can be used as a mining roadway for the adjacent working face in the future. The cutting roof and release pressure mining technology has changed the layout of the traditional long-wall mining side and the double-district roadway, creating a new method of digging a single lane.\textsuperscript{22} A comparison of the cutting roof and release pressure mining and the traditional longwall mining is shown in Figure 1.\textsuperscript{23}

3 | CAVING CHARACTERISTICS OF THE GOB UNDER THE ROOF CUTTING AND PRESSURE RELEASING MINING METHOD

3.1 | Movement law of overlying strata in the gob under the roof cutting and pressure releasing mining method

In the cutting roof and release pressure method, after the advanced blasting slitting is carried out, the surface of the slit
joint completely penetrates the immediate roof (as shown in Figure 2A). The immediate roof is separated from the floor by the advancement of the working face, and it caves from the middle of the working face to both ends. The roof along the gob-side roadway loses its supporting effect, and is affected by the bending and sinking of the overlying strata in the gob and the support in the lane. This causes it to break along the slit plane. During this process, the main roof gradually hangs, and after reaching the caving interval limit, fracture and sinking occur (as shown in Figure 2B).

3.2 Evolution of the overburden pressure in the gob under the roof cutting and pressure releasing mining method

After the coal seam in the working face is recovered, the overburden layer in the gob loses its support, and the immediate roof rock mass and some main roof rock masses in the coal seam are successively collapsed until the gob is filled. During the process of rock mass caving in the gob, the stress of the overlying roof is gradually transmitted to both sides, and the stress on the coal pillars or roadway roofs on both sides of the gob gradually increases. After the caved rock mass fills up in the gob, the stress of the overlying roof not only transfers to both sides continuously, but is also supported by the caved rock mass. Finally, the caved rock mass is compacted and restored to the support of the overlying roof. The stress transfer from the overlying roof to both sides is now complete, and the stress on the coal pillars or roadway roofs on both sides of the gob reaches a new equilibrium state.

4 Evolution law of the permeability characteristics of the gob under the roof cutting and pressure releasing mining method

As a caving space closely connected with the coal mining face, when we study the gob, it can be regarded as a whole research, that is, it consists of gas, coal rock solids, and voids between coal and rock bodies, and its internal medium is a void-rich caving rock body and working face residual coal. Compared with the entire gob, the gap between the caving rock and the residual coal in the working face is small, and the internal space is connected to each other. According to the definition of porous media, it can be considered that the caving rock in the gob and the residual coal in the working face have the characteristics of porous media, and the theory of porous media is used to study the law of gas flow in the gob.

4.1 Evolution law of the void rate in the gob under the roof cutting and pressure releasing mining method

As a porous medium area composed of the overburden caving rock and residual coal, the voidage and permeability of the gob are important parameters affecting the numerical simulation of the flow field in the gob. Therefore, we must conduct an accurate and in-depth study of the void ratio of the gob. To derive the regular expression of the void ratio of the gob, we simplify the gob model, as shown in Figure 3.

In Figure 3, $V_0$ represents the volume of the overburden strata to be caved in; $V_k$ represents the space volume of the idealized gob in the uncollapsed state of the overburden after the mining face has been mined; $V_m$ represents the collapse volume of the overburden; $V_n$ represents the volume of natural accumulation after overburden strata collapse; and $V_k$ represents the remaining volume of the idealized gob space after overburden strata caving and filling.

Here, we introduce the concept of the filling degree. The filling degree of the gob is the ratio of the natural
accumulation volume of the caving rock mass to the whole space volume of the gob after caving. It is denoted by $\eta$. The filling degree $\eta$ is as follows:

$$\eta = \frac{V_n}{V_m + V_n + V_k}$$

Porosity is the ratio of the volume of pore space to the total volume of porous media$^{26,27}$:

$$n = \frac{U_v}{U_b} = \frac{U_b - U_s}{U_b}$$

In the formula: $U_v$—the volume of the pore space, m$^3$; $U_b$—total volume, m$^3$; $U_s$—the volume of solids in the total volume $U_b$, m$^3$.

Here, we denote the void ratio of the gob as

$$N = \frac{U_v}{U_b} = \frac{U_b - U_s}{U_b} = \frac{V_m + V_n + V_k - V_m}{V_m + V_n + V_k} = \frac{V_n + V_k}{V_m + V_n + V_k}$$

In the formula: $N$—represents the void ratio of the gob; $U_v$—represents the volume of the void space in the gob, m$^3$; $V_m$—represents the total volume of the gob, m$^3$; $U_s$—represents the volume of solids in the total volume $U_b$ of the gob, m$^3$.

After the overlying strata of the gob are broken and collapsed, an irregular caving zone is formed by the free accumulation of broken rock blocks in the lower part of the gob.$^{28}$

However, the rock mass has a certain amount of dilatancy after fragmentation, and its fragmentation coefficient (the property of rock where its volume after fragmentation is larger than that before fragmentation,$^{29}$ usually expressed by the fragmentation coefficient) is as follows:

$$K_p = \frac{V_n}{V_m}$$

In the formula: $V_n$—representing the total volume of the fractured rock mass and the void space therein, m$^3$; $V_m$—represents the volume of the original rock, m$^3$.

Then, it is easy to obtain from Figure 3:

$$V_k = V_n + V_k$$

Equations (1) and (3) can be simplified by equation (5):
\[ \eta = \frac{V_n}{V_m + V_k} \quad (6) \]

\[ N = \frac{V_k}{V_m + V_k} \quad (7) \]

From Section 3, we see that in the initial mining stage, it is mainly the process of roof rock caving in the gob. This assumes that the advancing distance of the working face is \( L_0 \) when the roof of the gob fully collapses, and the initial mining stage is when the lagging working face distance of the gob is between 0 and \( L_0 \). During this stage, a part of the roof of the gob is in a state of suspension, because the caving rock mass has not completely collapsed. Consequently, the caved rock mass does not play a supporting role and is in a free and loose state. The void ratio of the gob at this stage is mainly related to the coefficient of shrinkage and the degree of filling. When the gob lags the working surface \( L_0 \), the caving rock mass in the gob reaches a complete collapse state. Eventually, as the working face advances, the degraded rock mass in the gob is compacted by the pressure of the overburden. The void ratio of the gob at this stage is mainly related to the coefficient of shrinkage. With the premise of ignoring the pores in the rock and only considering the gaps between the rock masses, \(^{30}\) by comparing the analytical Formulas (4), (6), and (7), the void ratio of the gob can be expressed as

\[ N = 1 - \frac{1}{K_p} \eta \quad (8) \]

In the formula: \( N \)—represents the void ratio of the gob; \( K_p \)—represents the coefficient of expansion of the rock mass; \( \eta \) is the degree of filling, taking a value between 0 and 1.

When \( \eta = 0 \), the rock mass has not yet collapsed, and the void ratio of the gob is 1; when \( \eta = 1 \), the rock mass has fully collapsed, and the void ratio of the gob is only related to the coefficient of expansion of the rock mass. The filling degree increases as the distance from the lag working surface increases. The distance between the filling degree and the lag working surface varies linearly. The expression of the filling degree and the lag working surface distance is as follows:

\[ \eta = \frac{L}{L_0} \quad (9) \]

In the formula: \( L \)—represents the distance of the lag working face, m; \( L_0 \)—representing the working surface advancement distance when the roof of the gob is fully collapsed, m.

Therefore, when analyzing the rock void fraction distribution in the gob for the roof cutting and pressure releasing mining method, the void rate of the gob is usually divided into two stages: insufficient collapse and sufficient collapse.

When the lagging working face distance of the gob is less than the full filling distance, the void ratio of the gob is mainly related to the fragmentation coefficient and filling degree. \( K_p \) takes the maximum value and can be obtained by field measurement.

When the lagging working face distance of the gob is more than the full filling distance, the void ratio of the gob is mainly related to the coefficient of expansion \( \eta = 1 \), and equation (8) is as follows:

\[ n = 1 - \frac{1}{K_p} \quad (10) \]

### 4.2 Evolution of permeability in the gob under the roof cutting and pressure releasing mining method

The gob is a porous medium. The gas flow pattern is a porous medium permeability. Most scholars regard Darcy’s law as the laminar law for porous media and use the macroscopic fluid mechanics theory and method to study the relationship between permeability, porosity, and particle size of a packed bed of granular media. \(^{31}\) For spherical particulate matter, the formula has the same form:

\[ e = \frac{D_p^2}{c} \times \frac{n^3}{(1-n)^2} \quad (11) \]

In the formula: \( e \)—represents permeability, m\(^2\); \( n \)—represents the porosity of the porous medium; \( c \)—represents a constant; \( D_p \)—represents the average particle diameter, m, which can be obtained from field observations.

For a constant \( c \), Ergun proposed a value of 150, while Bear proposed a value of 180. For different materials, the error in the approximate mean of the particle size may cause a constant definition of the difference. \(^{32,33}\) According to the experimental research by Blake Kozeny, it is more practical to take the random crushing stone constant value as 150. \(^{34}\) Using this value of \( c \) in equation (11), the formula becomes:

\[ e = \frac{D_p^2}{150} \times \frac{n^3}{(1-n)^2} \quad (12) \]

According to the research content in Section 4.1, the permeability of the gob can be obtained by equation (8):

\[ e' = \frac{D_p^2}{150} \times \left( \frac{1 - \frac{\eta}{K_p}}{\frac{\eta}{K_p}} \right)^3 \quad (13) \]
In the formula: \( e' \)—represents the permeability of the gob in the cutting roof and release pressure method mining, \( m^2 \).

When the lagging working face distance of gob does not reach the full filling distance, \( K_p \) takes the maximum value \( K_{p_{max}} \) and the permeability of the gob is obtained by the equations (13) and (9):

\[
\eta = \frac{D^2_p}{150} \times \left(1 - \frac{L}{K_{p_{max}}L_0}\right)^2
\]  

(14)

When the gob lags the working surface distance beyond the full filling distance, \( \eta \) takes 1, and then, the formula (13) can be expressed as

\[
e' = \frac{D^2_p}{150} \times K^2_p \left(1 - \frac{1}{K_p}\right)
\]  

(15)

When \( \eta = 0 \), the rock mass has not yet collapsed, the void ratio of the gob is 1, and the permeability of the gob tends to infinite; when \( \eta = 1 \), the rock mass has fully collapsed, that is, the state after the lagging working face distance of the gob reaches the full filling distance.

5 | APPLICATION OF THE EVOLUTION LAW OF PERMEABILITY CHARACTERISTICS UNDER THE ROOF CUTTING AND PRESSURE RELEASING MINING METHOD

5.1 | Engineering background

This paper is based on the 12 201 fully mechanized mining face of the Halagou Coal Mine, Shenhua Shendong Coal Group, Shenmu County, Yulin City, Shaanxi Province, China. The Halagou Coal Mine is located on the east side of the Ulan Mulun River, 55 km northwest of Shenmu County, Shaanxi Province, and 4.5 km north of Daliuta Town, Shenmu County, Shaanxi Province. There are eight layers of coal seams that can be harvested and partially mined. The main coal seams are 2-2 coal, 3-1 coal, and 4-2 coal, all of which are near-horizontal coal seams. The stratum generally has a monoclinic structure with a tendency toward SW, little undulation, and a dip angle that is generally less than 1°. The overall structure is simple with a small-scale normal fault in the southern part of the mine and no magmatic rock intrusion. The 12 201 fully mechanized mining face is the first mining face of the 12 coal two-panel area, and its arrangement is shown in Figure 4. The mining face is surrounded by the haulage roadway, the air-return roadway, and the open-off cut. The length of the working face is 320 m, the length of the open-off cut to stop the mining line is 747 m, the length of the roof cutting and roadway retaining section is 580 m, the thickness of the coal seam is 1.6-2.4 m, the average thickness of the coal seam is 1.9 m, the average mining height of the working face is 2 m, the mining volume is 610 000 tons, the coal seam is relatively stable, and to the northwest is the 12 202 working face. The 12 201 haulage roadway adopts roof cutting and pressure relief to retain the roadway, and the roadway has a rectangular cross-section (width \times height = 5.4 m \times 2.4 m). The depth of the fully mechanized mining face is 60-100 m, the thickness of the overlying bedrock is 55-70 m, and the thickness of the loose beds is 0-33 m. The bedrock is exposed on the surface of the area near the withdrawal passage. The immediate roof of the coal seam is siltstone, with an average thickness of 1.84 m; the immediate roof of the coal seam is 12 upper seams, with an average thickness of 1.56 m; the upper part of the coal seam is mudstone, with an average thickness of 1.35 m; the main roof is composed of fine-grained sandstone and siltstone, with an average thickness of 3.34 and 4.05 m, respectively; and the floor is siltstone, with an average thickness of 3.67 m.

Both the 12 201 and 12 202 working faces are naturally ventilated. The 12 201 working face uses a “U” ventilation method from the open-off cut 12 201 to the open-off cut 12 202. That is to say, fresh airflow enters from air-return roadway 12 201, flows through the working face, then enters haulage roadway 12 201, and flows out through open-off cut 12 202. After the working face is pushed through the open-off cut 12 202, the ventilation system will be changed to “Y” type. In other words, the 12 201 air-return roadway and the haulage roadway 12 201 are both air inlet roadways. The airflow in the 12 201 air-return roadway merges with the airflow of the haulage roadway 12 201 after it passes through the working face. Then, the confluent airflow continues to flow along the haulage roadway 12 201, and after that flows out through the open-off cut 12 202.

5.2 | Stress evolution of the overlying roof in the gob

The temporary support of the retaining roadway in Halagou Mine adopts the combined support mode of “single hydraulic prop + double T-steel + reinforcing mesh,” while a pressure measuring station near the gob side of the retaining roadway monitors the pressure change of the overlying strata near the gob side as the working face advances.

The monitoring data are taken at 205 and 73 m from the open-off cut 12 202 (the location of the monitoring points is shown as points B and A, respectively, in Figure 4), and the monitoring results are shown in Figure 5(A) and (B). In addition, the lateral pressure is measured at two locations on the
side of the gob roadway, 240 and 302 m away from the open-off cut 12 202 (the location of the monitoring points is shown as points C and D, respectively, in Figure 4). Monitoring the change in the lateral pressure of the retaining gangue support body in the retaining roadway section reflects the lateral stress and variation law of the caving rock mass in the gob. The results of the lateral pressure monitoring are shown in Figure 6(A) and (B).

It can be seen from Figure 5 that the overburden pressure in the gob is quite small in the initial stage, ranging from 18 to 26 MPa. When the working face begins to advance, the overburden pressure in the gob increases significantly, and rapidly increases from 32 to 36 MPa across a distance of 0-30 m behind the lagging working face, until it gradually stabilizes beyond 30 m. This is due to the large-scale movement of the overlying strata in the stope, which is caused by the coal seam mining on the working face and the continuous adjustment of the stress. As the working face and the support advance, the rear rock formation gradually loses its support. The gangue cut by the side roof of the gob in the retained roadway gradually collapses under the stress of the overburden strata and its own gravity and fills the gob due to fragmentation. With the mining of the working face, the roof rock mass of the gob near the working face is in
a collapse state, and part of the roof of the gob is in a suspension state. There is a certain gap between the immediate roof caving rock mass and the upper main roof rock stratum, which is influenced by the low stress in the gob and is not subject to the pressure or stress of the overlying rock stratum. Beyond a certain distance of the lagging working face, the gob collapses and is gradually compacted by the process of rotary subsidence of the main roof. During compaction, the roof pressure also increases significantly. When the lagging face distance is large, the roof pressure does not change, and the surrounding rock forms a stable structure.

Figure 6 indicates that the lateral stress of the gob is low in the initial stage, in the range of 0-0.4 MPa. As the working face begins to advance, the lateral stress growth in the gob experiences three stages: At a distance of 0-27 m from the lagging working face, the lateral stress of the gob increases by 0-1.6 MPa and is the rapid growth stage; the lateral stress growth of the gob is slow at a distance of 20-30 m, ranging from 0.48 to 1.65 MPa, and is the slow growth stage; at a distance of 25-39 m from the lagging working face, the growth rate is faster than the previous stage, ranging from 0.52 to 1.8 MPa, and is the secondary growth stage; it gradually stabilizes after 39 m. In the rapid growth stage and the slow growth stage, the roof gangue of the gob collapses and accumulates under the action of its own gravity, resulting in lateral stress acting on the roadway side; in the secondary growth stage, the gob has collapsed. The lateral stress of the gob increases significantly because the collapsed rock is affected by the stress of the overlying strata. When the distance from lagging working face is large, the roof pressure does not change, and the lateral stress of the gob tends to be stable.

5.3 Selection of the numerical simulation software and basic assumptions

Considering the example of Halagou Coal Mine, the gob is studied as a porous medium model. The ANSYS Fluent version 18.2 is selected as the numerical simulation software. Because of the complexity of its internal space, the following assumptions are made: (a) Assuming that the gas is incompressible, the gas flow is a steady state flow; (b) the influence of temperature change on gas flow in the gob is not considered; (c) because the geological structure within the working face of the test is simple and the dip angle of the coal seam is small, the entire coal seam in the gob is regarded as a horizontal treatment; (d) the incoming airflow is the fresh airflow, which does not contain gas; (e) the amount of gas emission from the coal wall of the roadway is neglected; (f) regardless of the actual shape of the equipment, such as the coal mining machine and the hydraulic support, the working face and the wind flow through the roadway are regarded as a rectangular parallelepiped, and the model parameters are set according to the actual parameters of the mining working face; and (g) the flow of air in the entry and return air roadways, and working face area is set as a turbulent flow, and the flow in gob area is set as a laminar flow.

5.4 Physical model, boundary conditions, and determination of some basic parameters

5.4.1 Physical model

The model intercepts the length of the gob by 400 m, the inclination length of the working face is 320 m, and the
rectangular section of the roadway has a width of 5 m and a height of 2.5 m. The numerical simulation model only considers the airflow movement inside the gob and does not consider the surface air leakage. The model of the gob is established as shown in Figure 7.

5.4.2 | Conditions of the model boundary

(1) Physical model.

The physical model uses the standard k-ε model of turbulence to better simulate the turbulent flow near the working face and the laminar flow inside the gob.35

(2) The boundary of the airflow inlet.

The boundary of the airflow inlet is set as the boundary condition of the velocity inlet. The total air distribution is 1162.5 m³/min. The wind speed of the airflow in the return airway 12 201 is 1.0 m/s, and the wind speed in the haulage gateway 12 201 is 0.55 m/s. The uniform airflow is vertical to the entrance of the intake roadway. When the wind speed is 0.55 m/s, the turbulent intensity and hydraulic diameter are set to 3.6944 and 3.3333, respectively. When the wind speed is 1.0 m/s, turbulent intensity and hydraulic diameter are set to 3.4288 and 3.3333, respectively. Turbulent intensity and hydraulic diameter are obtained by formulas (16) and (17).

(3) The boundary of the airflow outlet.

The airflow outlet boundary is set to outflow.

(4) Internal boundaries.

The boundary between the roadway and the gob is set to the interior surface, the fluid can flow freely and the remaining unset boundaries default to walls. All the walls are conditional without slipping, and the near wall of the working face is treated by the standard wall function method and with heat insulation.

(5) Setting of porosity and viscosity resistance coefficient.

In this study, parameters such as the filling degree, coefficient of expansion, permeability, and average particle diameter of the gob are written into the UDF and loaded into the Fluent solver to obtain the void ratio and viscous drag coefficient of the gob.

(6) Setting of viscosity resistance coefficient.

In Fluent, the gob is considered as a continuous heterogeneous porous medium region, and the additional resistance to gas flow in the gob is indicated by an additional momentum loss source term in the standard momentum equation.36 The basic form is as follows 37:

$$I = 0.16 \times Re^{-0.5}$$

$$Re = \frac{vD_H}{\nu}$$

Here, \(I\) is the Turbulent Intensity, %; \(Re\) is the Reynolds number; \(v\) is the mean velocity of the object relative to the fluid, m/s; and \(\nu\) is the kinematic viscosity, m²/s. The kinematic viscosity of air is \(14.8 \times 10^{-6}\) m²/s.

$$D_H = \frac{4S}{L}$$ (17)

Here, \(D_H\) is the Hydraulic Diameter, m; \(S\) is the roadway section area, m²; and \(L\) is the roadway circumference, m. \(S\) and \(L\) can be calculated from the width and height of the roadway.
In the formula: \( \sum_{j=1}^{3} D_{ij} \mu v_j \) —represents the loss of viscosity; \( \sum_{j=1}^{3} C_{ij} \frac{1}{2} \rho v_j \) —represents the loss of inertia; \( S_i \) —represents \( i \) direction (x, y or z) momentum equation source term; \( \mu \) —represents the viscosity of dynamic, Pa·s; \( v_j \) (\( j = 1, 2, 3 \)) —represents the velocity component of the fluid microelement in the x, y, z direction, m/s; \( \rho \) —represents the density of fluid, kg/m\(^3\); \( D_{ij} \) —represents the loss coefficient of viscous resistance; \( C_{ij} \) —represents the loss factor of inertial resistance.

Because the air leakage velocity in the gob is small, the inertia resistance term is usually neglected, and the momentum loss is mainly provided by the viscous resistance term.\(^{38}\) The viscous resistance coefficient \( D \) and the permeability of the gob are reciprocal, and the viscous resistance coefficient on the fluid microelement is regarded to be isotropic. Consequently, equation (16) can be simplified as follows \(^{39}\):

\[
S_i = \frac{1}{\varepsilon} \mu v_i (i = x, y, z)
\]  

(17)

In the formula: \( \mu \) —represents the viscosity coefficient of air, \( \mu = 1.7894 \times 10^{-5} \) kg/(m·s); \( \varepsilon \) —represents the permeability of the gob in the method of cutting roof and release pressure, m\(^2\).

5.4.3 | Determination of some basic parameters

From field measurements and observations, the maximum value of \( K_p \) is 1.88 and the value of \( D_p \) is 0.3 m.

From field measurements, the relationship between the coefficient of expansion of the obtained rock mass and the distance of the lag working surface is shown in Figure 8.

After fitting, the relationship between \( K_p \) and the lag working surface distance is as follows:

\[
K_p = 1.36 + 0.67 \times 0.96^L
\]  

(18)

5.5 | Law of airflow movement along the side of the retaining roadway

The difference between the contours of the flow function represents the flow of fluid passing between the two contours. Using the postprocessing function in Fluent, the curve of the change in the boundary flow function along the direction of the retaining roadway is plotted, as shown in Figure 9. From the figure, it is clearly visible that the airflow escapes from the gob retaining roadway.
to the retaining roadway or vice versa in the direction of the entire roadway. The distribution of the airflow from the gob to the retaining lane or vice versa is plotted in Figure 10, where a positive value of air leakage represents the airflow from the gob to the retaining roadway, and a negative value represents the airflow from the retaining roadway to the gob. The location of this distribution in the gob is shown in Figure 11.

In Figure 10, the total air volume that escapes from the gob to the retaining roadway is 318.64 m$^3$/min and the total air volume that escapes from the retaining roadway to the gob is 31.72 m$^3$/min. From 22 to 398 m along the direction of the retained roadway, which is 94% of the total length of the retained roadway, the maximum amount of air escaping from the gob into the retained roadway is 309.38 m$^3$/min, accounting for 97.1% of the total amount of air escaping from the gob into the retained roadway. This shows that there is air escaping along the entire retained roadway section and the total amount of air escaping is considerable, because the gob is an open mining area with the Y-type ventilation mode of a roof relaid roadway. From 6 to 16 m, the airflow from the gob to the retaining roadway is 9.25 m$^3$/min, accounting for 2.9% of the total airflow into the retaining roadway. Since there are parts of the airflow from the retained roadway to the gob before and after the scope, the airflow into the retained roadway may also be caused by the influence of the eddy current area. From the ranges of 0-6, 16-22, and 398-400 m, a part of the airflow escapes from the retained roadway to the gob, but the volume of airflow is low at 3.74, 1.64, and 26.34 m$^3$/min, respectively. These values account for 11.8%, 5.2%, and 83% of the total airflow from the road to the gob, respectively. The large proportion of airflow from 398 to 400 m is because the air gathered in the gob retaining roadway needs to turn through the place to flow into the return air roadway, and the resulting eddy current forms a part of the airflow to the gob.

To obtain the detailed airflow conditions in the roadway, we define the amount of air leakage per unit distance in m$^3$/min-m. When the air leakage volume per unit distance is positive, it represents the amount of air escaping from the gob into the retaining roadway per meter, and when it is negative, it represents the amount of air escaping from the retaining roadway to the gob per meter. A plot of the air leakage per unit distance in the direction of the retaining roadway is shown in Figure 11.

As shown in Figure 11, the air leakage per unit distance is stable from 100 to 390 m along the roadway. The zone where the air leakage per unit distance of the roadway is stable is called the roadway airflow stability zone. The air leakage per unit distance in the stable area of the roadway airflow movement is still small. The volume of air escaping from 100 to 390 m is 123.79 m$^3$/min, accounting for 38.8% of the total air volume escaping from the gob. From 22 to 100 m and from 390 to 398 m, the volume of air escaping from the gob into the retained roadway is larger, 138.33 and 49.1 m$^3$/min, respectively, accounting for 43.4% and 15.4% of the total amount of air escaping from the gob into the retained roadway, respectively. These two zones are called critical zones in which the airflow from the gob to the retained roadway mainly concentrates at 22-100 m. Within this range, the air leakage per unit distance increases sharply from 22 to 30 m and decreases gradually after reaching 30 m. The main reasons for this behavior are as follows: Part of the roof of the gob from 22 to 30 m is in a state of suspension, and the caving rock mass has not yet completely collapsed. At this time, the gob has large voids and serious airflow migration; beyond 30 m, the pressure of the overlying strata in the gob tends to stabilize gradually, and the caving rock mass in the gob has completely collapsed and gradually compacted under the pressure of the overlying strata. The cracks in the inner part of the gob and the airflow volume are then gradually reduced. The area with the highest airflow transport from 22 to 100 m is in the range of 28-53 m. The airflow transport volume in this area is 80.55 m$^3$/min, accounting for 43% of the total air inflow in the two serious air leakage areas and nearly 60% of the airflow transport volume from 22 to 100 m.

From 0 to 22 m and from 398 to 400 m, the air leakage per unit distance fluctuates greatly due to the influence of eddy currents in both areas. These two areas are called the eddy current influence areas of the retained roadway. The area from 0 to 22 m lies at the intersection of two inlet eddy currents, and the air leakage per unit distance fluctuates greatly and is extremely unstable. The air leakage per unit distance from 398 to 400 m range is negative, which indicates that air escapes from the retained lane to the gob, the volume of which is 26.34 m$^3$/min.

### 5.6 Engineering practice effect

The 12 coal seam of Halagou coal mine has a spontaneous combustion period of 1-3 months and belongs to spontaneous...
combustion coal seam. All 12 upper coals were left in the gob of 12 201 working face during the mining process. The spontaneous combustion in the gob of 12 201 working face is more serious. The 12 201 working face started mining in July 2015 and completed mining in December 2015. When the working face was advanced 346 m, the CO concentration in the gob reached 326 ppm. The CO concentration in the gob was always kept below 300 ppm after taking comprehensive antileakage measures. The validity of the numerical simulation results is verified through the realization of safe mining in the 12 201 working face.

The findings of this work are inspiring in the implementation of antileakage technology in the gob. According to these findings, targeted measures can be taken for the air leakage area of the gob under the roof cutting and pressure releasing mining method to effectively prevent the spontaneous combustion of the leftover coal caused by fresh airflow from the roadway into the gob.

6 | CONCLUSION

To analyze the permeability characteristics of the gob for the roof cutting and pressure releasing mining method, a mathematical model for the gob voidage and permeability was established. Then, the fluent software combined with the established mathematical model was used to study the airflow migration law of haulage roadway 12 201 in Halagou. The main conclusions are as follows:

1. The overburden pressure in the gob is small at the initial stage at approximately 18-26 MPa. When the working face starts to advance, the overburden pressure in the gob increases rapidly in the lagging working face from 0 to 30 m until it reaches 32-36 MPa. Beyond 30 m, the pressure gradually becomes stable.
2. The increase of lateral pressure in the gob goes through three stages: rapid growth, slow growth, and secondary growth. The lateral pressure of the gob gradually stabilizes after 39 m of the lagging working face.
3. According to the characteristics of gob caving, the concept of the filling degree is introduced, and the voidage evolution model and permeability evolution model, including the breaking expansion coefficient and filling degree of the gob caving rock mass, are constructed.
4. Along the direction of the roadway, there are two critical zones where the airflow escapes into the retaining roadway: the 22-100 m and 390-398 m sections. The airflow in these two areas accounts for 59% of the total airflow in the retaining roadway. Of the two, the 28-53 m section is the most serious, and its escaping air volume accounts for approximately 43% of the total inflow of the two severely leaking sections.

Thus, this research provides a theoretical basis for the implementation of antileakage technology in the gob under the roof cutting and pressure releasing mining method and helps reduce the risk of spontaneous combustion in the gob. However, this work used a two-dimensional model for physical modeling, not considering the differences in the vertical parameters of the gob. In the future research, a three-dimensional model should be established for simulation analysis to obtain more accurate simulation results.

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CONFLICT OF INTEREST
None declared.

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