Study on the pressure relief effect in gob-side coal body during mining an inclined longwall panel

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Abstract
This study combined multi-field coupled numerical calculations and field measurements to analyze the gas pressure relief and the outburst elimination range of the coal body in the lower side of a gob induced by excavating an inclined seam. A coal seam gas flow solid-gas coupled model allowing for elastoplastic damage was established based on an inclined longwall panel of the Hongyan Coal Mine in Chongqing, China. To inspect the gas depressurization effect, this study simulated the collapse and damage of strata surrounding the longwall panel after mining by using a constitutive model of the interlayer weak plane, the changes in the damage, gas pressure, and stress concentration in the gob-side coal seam were analyzed numerically. Besides, variation in gas pressure within 10-23 m away from the panel margin was measured on-site during the advancement of the longwall face to validate and modify the results of modeling. The simulation results showed that the advancing of the panel is highly effective in releasing gas from the gob-side coal body. The rupture penetration, stress concentration, and original elastic zone will be formed in the gob-side coal body with increasing distance away from the gob after mining the 3603-2 panel. The permeability increased dramatically and the gas was almost exhausted in the rupture penetration zone. The field measurement results indicated that gas pressure decreased in three stages with advancement. After completion of excavation activities, the drop rates of gas pressure and gas content within 10-23 m from the gob were 26.55%-73.58% and 34%-71%, respectively. Additionally, it was proved that the numerical simulation results were instructive for predicting the range of gas outburst-proneness elimination belt by comparing simulation and field results, and the outburst elimination range of the inclined longwall panel of the Hongyan Coal Mine was determined to be 10 m.

KEYWORDS
gas pressure relief, inclined seam, numerical simulation, outburst elimination range
INTRODUCTION

Coal is the primary energy source in China, with utilization accounting for up to 70% of national energy consumption.\(^1\) Coal resources near the surface in China are rapidly exhausting because of huge coal consumption, resulting in the depth of coal mines extending downward at an annual rate of 10-50 m.\(^2\) As the depth increases, the coal seam gas content and pressure rise gradually, in turn increasing the challenges associated with mining safety, and in particular gas-related accident prevention. Gas-related incidents can occur during both coal roadway (headgate and tailgate) tunneling and subsequent mining,\(^3\) especially the tunneling activities accounting for the majority of incidents.\(^4\) When coal and gas outbursts (CGO) occur, they often cause a large number of casualties and heavy economic losses. Due to these risks, it is necessary to ensure that the coal body on both sides of the roadways has a sufficiently safe distance apart to minimize outbursts, and regional outburst prevention measures should be taken with guidelines provided by the relevant safety regulations of China. In the single-layer coal seam mining, the pressure relief effect of protective coal layer extraction is inefficient,\(^5\) the required safe distance is usually achieved by predraining coal seam gas from roof/floor rock roadways. During the mining of inclined seams, chain pillars are often left in place to prevent water and gangue from running down to the lower section working face during advancement. Due to the existence of the coal pillars, the outburst elimination range achieved by predrained gas may not meet requirements when heading the tailgate of the lower section panel.\(^6\) To determine the minimum safe distance, it is necessary to ascertain the gas occurrence that is present at the coal pillar. However, the occurrence of coal seam gas in the lower section is associated with mining of the upper section working face, which subjected to the following key aspects: (a) Before excavation of the roadway of an upper section working face, gas in this area is predrained to ensure the safe working distance requirements. (b) After excavating the roadway in the upper working face, the roadway can be regarded as a large-diameter discharge borehole, providing an outlet for gas flow. (c) After mining of the upper section panel is completed, the gob-side coal mass in a limited range will suffer plastic failure, which increases the coal seam permeability allowing gas to flow more readily to the gob. These features will assist in outburst-proneness elimination (OPE).

Mining activity induces the stress redistribution, and subsequent deformation, damage, and fracturing in surrounding coal and rock mass, and these effects will change the gas occurrence in the gob-side coal body. Over the years, many researchers have done large amounts of instructive research in this field, and drawing some important conclusions. It is generally accepted that the abutment stress will vary with distance from the panel and can be divided into stress decreasing, stress increasing, and original stress zones. As the stress zones in front of the coal face will move dynamically with the advancement of the working face, the stress peak moves deep into the seam.\(^7\)-\(^10\) The evolution of the mining stress field is also correlated with the failure of coal and rock mass during the mining process.\(^11\) Xu et al.\(^12\) found that the rupturing key strata have a significant impact on the abutment stress of the coal rib, with the abutment stress reaching maximum and then sharply decreasing before and after rupture. Before overburden strata are cracked, deflection and subsidence deformation will occur and the uncoordinated deformation will induce the separation of strata and the formation of a fracture network. Many studies proposed that with the advancement of the working face, a fracture network is propagated in the overburden strata, the microscopic fracture which is generated in initial stage extend to macro fracture network, and it spreads forward as the working face advancing.\(^13\)-\(^15\)

Few studies focused on the impact of mining on gob-side coal mass. Zhu et al.\(^16\) determined that the maximum vertical stress in the center of a gob-side coal pillar increases with the width of the coal pillar. Wang et al.\(^17\) concluded that the features of abutment stress at the lateral strata of gob show five stages along the strike, and five interval characteristics along with the dip as used by a method of the on-site survey. Wang et al.\(^18\) reported that the distance between the location of the stress peak and the panel margin increases with the advance of the working face. Xu et al.\(^10\) also concluded that the influence range caused by relaxations on both roadways is also increased with the advancement of the working face. In order to further understand the influence of working face mining on gob-side gas emission, it is necessary to study the change of stress, damage, and permeability of coal and rock around gob, and how these factors affect the gas parameters. This will identify the range of OPE, provide a reference for the layout of the gob-side roadway and design of the chain pillar, as well as improve procedures for supporting outburst prevention.

Despite the advances in understanding the mining effect to strata geomechanics, there is a lack of reported information focusing on gas emission in gob-side coal body under the influence of mining. This study investigates the evolution law of gas flow and its influencing factors in the gob-side coal body under the mining disturbance. A solid-gas coupled model is presented to describe the coal seam gas flow based on mining of the 3603 longwall panel located at the Hongyan coal mine in Chongqing, China. Deformation and failure characteristics around the gob, stress distribution and permeability change in gob-side coal seam are determined by numerical calculations. Field measurements are implemented to monitor coal seam gas pressure within 10-23 m of the gob-side coal seam during the advancement of working face over 380 days, and the monitored data are analyzed to conduct the variation law of the gas parameter with the advancement of
the panel. By comparing the numerical simulation and field investigation results, the gas emission law, and the width of the OPE zone in the gob-side coal seam are determined and presented.

2 | SOLID-GAS COUPLED THEORY OF GAS MIGRATION IN COAL

The solid-gas coupled model presented in this study was constructed based on the following assumptions (within the accuracy of current engineering practices): (a) Coal is a porous medium, and it also has continuous, homogeneous, and isotropic properties. (b) The gas contained in the coal body is either free or adsorbed and absorbed gas in the coal seam, the adsorbed and absorbed gas is subjected to Langmuir law while free gas satisfies the ideal gas state equation. (c) Darcy's law is used to describe the gas seepage through a coal seam and there is no effect from gravity.

2.1 | Theory of gas migration

Gas migration in coal can be expressed by the following formula (Equation 1) according to the law of conservation of mass:

$$\nabla \cdot (\rho_g v_g) + \frac{\partial C}{\partial t} = 0 \tag{1}$$

where $\nabla \cdot$ represents divergence, $\rho_g$ is gas density, kg/m$^3$; $v_g$ is gas flow velocity, m/s; $C$ is gas mass content, kg/m$^3$; and $t$ is gas flow time, s. Assuming that any gas seepage complies with Darcy's law and ignoring the influence of gravity, $v_g$ in Equation (1) can be expressed as follows:

$$v_g = \frac{-k}{\mu} \nabla p_g \tag{2}$$

where $k$ is the effective permeability of coal seam gas, m$^2$; $\mu$ is dynamic viscosity, Pa s; $p_g$ is the coal seam gas pressure, Pa; and $V$ is the notation of the gradient.

Existing research shows that gas present in coal is composed of both free and adsorbed phases. The ideal gas state equation can be used to calculate the free gas content in coal pores, and as the content of adsorbed gas follows the Langmuir equation, the gas mass content $C$ can be expressed as follows:

$$C = C_{ad} + C_{free} = (1 - A - M)\rho_c \rho_g \frac{ab p_g}{bp_g} + p_g \beta_g \varphi \tag{3}$$

where $C_{ad}$ is the content of adsorbed gas, $C_{free}$ is the content of free-phase, $A$ and $M$ are ash and moisture content, $a$ is the Langmuir adsorption volume constant in units of m$^3$/kg, which is an indication of the gas adsorption capacity limit of the coal sample, $b$ represents the Langmuir adsorption pressure constant, $\rho_c$ is the density of coal, kg/m$^3$; $\varphi$ is the porosity of coal, $\beta_g$ is the gas compression factor, when assuming that the gas is ideal, $\beta_g = M/RT$, $M$ is the molecular weight of the gas, $R$ is the universal gas constant and $T$ is the absolute temperature.

2.2 | Theory of solid deformation

Combining the motion equilibrium equation of gas-containing coal, Terzaghi effective stress principle, and Hooke's law, the following equation can be used to express the constitutive relation of isotropic linear poroelastic media:

$$\sigma_{ij} = 2G\varepsilon_{ij} + \frac{2G}{1 - 2v}\varepsilon_{kk}\delta_{ij} - \alpha p_S \delta_{ij} \quad (i, j = 1, 2, 3) \tag{4}$$

where $\sigma_{ij}$ and $\varepsilon_{ij}$ are stress tensor and strain tensor, respectively, $G$ is the shear modulus, $v$ is the Poisson's ratio of coal, $\delta_{ij}$ is the Kronecker delta, $\alpha$ is Biot's coefficient and $\alpha = 1 - K/K_S$ , $K$ and $K_S$ are bulk modulus of a porous framework and bulk modulus of coal matrix, respectively, and $\varepsilon_{kk}$ is the volumetric strain which can be presented as:

$$\varepsilon_{kk} = \varepsilon_v = \frac{1}{K}(\overline{\sigma} + \alpha p) \tag{5}$$

where $\overline{\sigma}$ is the mean stress and equal to $\sigma_{kk}/3$.

2.3 | Damage-permeability evolution model

2.3.1 | Porosity-permeability equations

Permeability is a key parameter reflecting the difficulty of gas migration.\textsuperscript{19} The permeability in a conventional gas reservoir is usually considered constant,\textsuperscript{20,21} but during the seepage process of coal, the gas permeability will change significantly with the stress, pressure, and deformation of the coal body. The influence of these factors on the permeability of coal seams makes the seepage of gas a prominent fully coupled multi-physics process.\textsuperscript{22-24} The cubic law is widely used to determine the relationship between the porosity and permeability of coal,\textsuperscript{25-27} and we also utilize the cubic law to describe these phenomena (Equation 6):

$$k_i = k_0 \left( \frac{\varphi}{\varphi_0} \right)^3 \tag{6}$$
where \( k \) and \( k_0 \) are the absolute and initial permeability, \( m^2 \); \( \varphi_0 \) is the initial porosity, \%; \( \varphi \) is the porosity of coal, \%, which varies with the volume strain affected by the stress field. Taking the gas pressure and stress into account, the general porosity model can be defined as follows:\(^{28}\):

\[
\Delta \varphi = \frac{1}{K}(\alpha - \varphi)(\bar{\sigma} + p_g)
\]  

(7)

where \( \Delta \varphi \) is the change in coal porosity, \%. By substituting Equation (5) into Equation (7), it can be found that:

\[
\Delta \varphi = \frac{1}{K}(\alpha - \varphi) \left( \varepsilon_v + \frac{p}{K_S} \right)
\]  

(8)

Based on the assumption that the initial porosity is \( \varphi_0 \), the initial gas pressure is \( p_0 \) and the initial volumetric strain is zero, \( \varphi \) (the porosity of coal) can be represented as:

\[
\varphi = \frac{1}{1 + S}(1 + S_0)\varphi_0 + a(S - S_0)
\]  

(9)

where \( S = \varepsilon_v + \frac{p}{K_v}, S_0 = p_0/K_v \). If we differentiate \( \varphi \) with time, the following is obtained:

\[
\frac{\partial \varphi}{\partial t} = \frac{a(1 + S) - [(1 + S_0)\varphi_0 + a(S - S_0)]}{(1 + S)^2}
\]  

(10)

Although it is possible to use Equations (6) and (10) to describe the evolution of coal permeability under elastic deformation, mining activity in practice usually causes serious damage around the working face and the permeability of the damaged area will increase sharply. Therefore, it is necessary to develop and introduce a new model to describe the permeability change during the process of coal mining.

2.3.2 Damage-permeability model

During the advancement of the working face, the vertical stress of overlying strata transfers to the surrounding coal and rock mass of the gob. This leads to an increase in stress and plastic failure within a certain range of the gob, with these stresses altering the coal seam permeability and affecting the gas flow field around the working face.\(^{29}\)

The plastic failure of the coal or rock mass is typically determined by yield criteria, such as the Mohr-Coulomb (M-C), Drucker-Prager (D-P), and Hoek-Brown (H-B) criteria. Compared to the M-C and D-P criteria, which usually overestimate the tensile strength of the rock mass, the H-B criterion is a nonlinear semi-empirical strength criterion for geological materials, and it can easily establish the relationship between the mechanical parameters of a geological sample and those of the rock mass on-site through simple laboratory tests and on-site field observations. It is widely used and accepted in the geomechanics industry.\(^{30,31}\) In this study, the Hoek-Brown plastic yield criterion\(^{32}\) is used to describe the plastic failure of coal and rock mass after damage caused by mining (stresses are positive in tension). Equation (11) describes this relationship:

\[
\begin{align*}
    f &= \sigma_1 - \sigma_3 - \sigma_{ci} \left( s - m_b \frac{\sigma_1}{\sigma_{ci}} \right)^a \\
    a &= 0.5 + \frac{1}{6} \exp \left( \frac{GSI}{15} - \exp \left( -\frac{20}{3} \right) \right) \\
    s &= \exp \left( \frac{q}{GSI - 100} \right) \\
    m_b &= m_{max} \exp \left( \frac{GSI - 100}{28} \right)
\end{align*}
\]  

(11)

where \( \sigma_1 \) and \( \sigma_3 \) are the maximum and minimum principal stress, respectively, \( \sigma_{ci} \) is the uniaxial compressive strength; \( s, a \), and \( m_b \) are the Hoek-Brown constants; \( GSI \) is the geological strength index.\(^{33}\) According to the plastic theory, deformation will occur after the material reaches its stress peak. It is expectable that a dramatic increase in material results from deformation-induced micro fractures. Thus, a coefficient reflecting the change in permeability caused by plastic strain is introduced to establish the relationship between the plastic deformation and coal permeability:\(^{34}\):

\[
k = k_f(1 + D\zeta)
\]  

(12)

where \( k \) is the apparent permeability coefficient, \( m^2 \); \( \zeta \) symbolizes the coefficient of a sudden increase/decrease in gas permeability in the plastic zone; \( D \) represents a damage-like variable and \( D = \frac{\bar{\varepsilon}_p}{\varepsilon_{p, \text{max}}} \), in which \( \varepsilon_{p, \text{max}} \) is the limit plastic strain; \( \bar{\varepsilon}_p = \sqrt{2/3} \varepsilon (\varepsilon') \varepsilon'' \) is the effective plastic strain, if \( \bar{\varepsilon}_p > \varepsilon_{p, \text{max}} D \) equals one.

The coefficient form of the second-order partial differential equation is obtained by arranging Equations (1) and (3):

\[
\nabla(\text{coeff}_a \nabla p_g) + \text{coeff}_b \nabla p_g + \text{coeff}_c \frac{\partial p_g}{\partial t} = 0
\]  

(13)

where \( \text{coeff}_a = \beta_a \frac{\partial p}{\partial t}; \text{coeff}_b = -\frac{\beta_a k}{\mu}; \text{coeff}_c = \frac{(1 - \lambda - M\beta_2 \rho_g \rho_k)}{(1 + \beta_p \rho_g)^2 + \beta_0 \rho_k}. \)

Owing to the complexity of the above equations, the solids-gas coupled model is solved numerically.

3 NUMERICAL STUDY

3.1 Engineering background

The Hongyan Coal Mine is located in the south of Chongqing, China. It has only a single mineable coal seam
(6#), which is mined using the longwall method. The average angle of inclination and thickness of the seam is 30.5° and 1.8 m, respectively. It is a high-sulfur and high-calorific value fertilizer coal. This coal seam is prone to gas outbursts, with the original gas content and pressure 10.02 m³/t and 3.18 MPa when measured at +0.362 m elevation (buried depth 540 m) near the 3603-2 panel. The elevations of the 3603-2 tailgate and headgate are +100 and +10 m, and the vertical height of the longwall panel is 90 m. The longwall face of the panel is pseudo-inclined and its true angle of tilt is 23°.

To block water and gangue of the 3603-2 gob when mining the lower section panel 4603, a small wide chain pillar is required to be kept. A reasonable width coal pillar can ensure there is enough safe distance from the upper section gob and provide a reference for the arrangement of OPE in the process of tunneling the tailgate. To determine the OPE, boreholes were arranged 10-23 m away from the gob-edge to monitor the changes in the gas pressure in front of the 3603-2 working face during its advancement. The monitoring data were used for validation and comparison with the numerical calculation results.

3.2 | Numerical model setup

As the coal seam of the 3603-2 panel is inclined, a three-dimensional model is required to be prepared for simulating the advancement of the panel. However, this is problematic due to the coal seam thickness (1.4 m) being significantly smaller than the longwall face length (160 m) and the advancement distance, a large number of elements will be generated if a three-dimensional model is used for the numerical calculation, requiring excessive computing power. Therefore, a simplified two-dimensional plane strain model was utilized to reduce the solving scale. To negate the impact of boundary effects on the simulation results, the width and height of the geometry were set as 410 and 430 m, respectively (Figure 1), as per standard engineering practices.

Due to the simplification from a 3D to a 2D plane strain model, it is impossible to calculate the equations of gas seepage during the advancement of the working face. Consequently, the influence of the dynamic stress which is induced by advancing the working face on the gas seepage field must be ignored. To simulate the scenario as realistically as possible, the initial stress conditions of the gas seepage field are set the same as the stress equilibrium state after mining the panel. Moreover, the initial gas pressure is determined according to the field measurement during the study.

Mining will inevitably cause plastic damage to the surrounding coal and rock mass, and the permeability will increase by orders of magnitude as a result, and it is necessary to consider this effect. In this study, a self-defined constitutive model of coal and rock based on the H-B plastic yield criterion is adopted. Concurrently, each rock stratum is connected by a special weak plane material to virtually simulate the separation phenomenon of weak planes between strata during mining. This can be implemented by deleting the material from the model when the normal stress of the material is greater than 0 (tension). Existing computer software cannot customize the constitutive model and carry out a multi-field coupled calculation at the same time, hence this study combines the numerical software LS-Dyna and COMSOL to solve the model.

The process of solving the model is as follows: Firstly, the Development template of the user-defined material model provided by LS-DYNA was utilized to implement the secondary development. After entering the first level subroutine, the secondary material subroutines are selected according to model unit types, and then the elastoplastic damage constitutive model of rock material based on the H-B plastic yield criterion were compiled in the three-level user subroutine. At the same time, the material description including Elastic modulus, Poisson’s ratio, and other parameters was given in the corresponding K file. Secondly, the self-defined model was used to solve the stress-strain field of the working face after mining the panel. Thirdly, the partial differential equation of the damage-permeability model (Equation 13) was defined based on the COMSOL’s PDE mode. Finally, the stress and damage variables calculated by the Ls-Dyna were imported to COMSOL multi-physics software to solve the solid-gas coupled model, the stress calculated in LS-DYNA
was taken as the initial stress condition in COMSOL, and the damage variable was imported by interpolation.

The geometry and mesh of the calculation model are presented in Figure 1, with the model was divided into 128,969 elements. The thickness of the weak-layer elements inter-strata was set to 0.05 m, which was a rectangular plane strain element. This will be deleted if the principal stress of the elements along the normal direction of the layer is greater than zero. After the inter-layer elements were deleted, the contact algorithm was used to simulate the closure of the rock strata. Triangular plane strain element was adopted for the rest elements of the model, to improve the accuracy of the solution, the element size in the area near the working face was decreased to a maximum size of 0.3 m.

To compensate for the seepage effect of the roof and floor, the two floors and three roofs in direct contact with the coal seam were set to calculate the gas emission of the floor-coal-roof system. For the seepage field, all the external boundaries of the model were assumed to be nonflow, and the gas pressure at the working face was 1 atm. The physical and mechanical properties of rock strata and weak interlayers of the model were set to the weighted average values of the strata. The Langmuir coefficients were obtained experimentally and the parameters of the model were presented in Table 1.

### 4 | FIELD MEASUREMENTS OF GAS PRESSURE CHANGES IN GOB-SIDE COAL BODY

#### 4.1 | Site and drilling layout

Coal seam gas pressure is an important parameter to evaluate the potential risk of CGO. Considerable experimental and theoretical researches have improved the techniques for undertaking accurate measurements of gas pressure. In order to investigate the gas pressure in the gob-side coal body varying with the advancing distance, the measurement site was set in the middle of the mining panel, where is 100 m ahead of the 3603-2 working face. Considering that if the distance from the coal wall is too close, the coal body will be destroyed; too far, the coal will not be affected by the pressure relief, thus, the boreholes would be drilled within 10-23 m from the inclined length of the panel headgate.

Three groups were set to make sure that the measured data are adequate and reliable, and the groups were spaced 20 m along the strike. Four measured points in each group were needed to monitor the variation of gas pressure at different distances from gob, and the distances between the edge of the gob and boreholes in each group were set as 10, 15, 20, and 23 m, respectively. In order to minimize the interaction between the pressure measurement spot, the straight-line distances among these boreholes were kept at least 5 m, therefore, the last measurement point in each group was spaced 10 m away from the other three along the strike (Figure 2A,B).

#### 4.2 | Observation and recording

Twelve gas pressure gauges were arranged in the field to monitor pressure at different positions from the gob during the advancement of the working face. The time interval between measurements varied, depending on the status of working face advancement. Gauge pressure was nominally recorded every 5 m (normally about a week) during the initial stage of advancing. When the distance between boreholes and advancing face was less than 30 m, the measurement frequency was increased to every 2-3 m of advancement (about every 3-4 days). When the working face had passed the boreholes by more than 100 m, the frequency of measurement was reduced to once every 30 m.

Before the working face was pushed forward, the initial gas content was measured by sampling boreholes. The residual gas content would be determined by sampling at 10, 15, 20, and 23 m away from the gob-edge 380 days after mining.

### 5 | RESULTS AND DISCUSSION

#### 5.1 | Numerical results

5.1.1 | Deformation and failure characteristics around the gob

Figure 3 demonstrates the displacement and damage distribution of coal and rock around the working face after the excavation of the panel. In Figure 3A, the middle overlying
Strata are seen to bend downward and settle, with a maximum displacement of 2.89 m. The overlying strata slip down along the bedding plane between the weak interlayers. The roofs are seen to collapse and fill into the gob, with the resultant displacement of the bottom strata gradually decreasing along the inclined direction, while the displacement of the middle strata decreases from the middle to both sides.

The distribution of damage of the overlying strata is trapezoidal, as seen in Figure 3B. The most seriously damaged zones are located in the middle and lower strata and the coal seam near both sides of the gob. Under the actions of both tensile and shear stress, the damage accumulation in the lower part of the overlying strata leads to the fracture separation, and a penetrating fracture appears in the middle rock strata. It is demonstrated that the coal seam near the abandoned headgate is crushed under the concentrated load resulting from the excavation of the panel. This would result in an interconnected fracture network forming in the coal seam, providing channels for gas flow through to the gob.

The equivalent stress distribution cloud diagram of the surrounding coal and rock after mining is presented in Figure 4. The vertical stress induced by the weight of the overlying strata will transfer to the surrounding rock or coal of the gob, resulting in the high-stress concentrations near the gob edges and the stress-relief areas in the middle of the mined-out panel. The stress concentration is prevalent on both the upper and lower sides of the panel. The maximum point of equivalent stress is located in the strata contacted directly with the coal seam, and the equivalent stresses on both sides of the gob decreased gradually toward the roof and the floor. However, the equivalent stress distribution on the lower side along the dip of the working face is wider and larger than that on the upper side, which may be resulting from the vertical stress of the overlying strata near the lower of the gob being larger than that of the upper gob. The shape of the stress-relief area is an asymmetric trapezoid in the middle of the overlying strata and the stress distribution shows obvious delamination.

5.1.2 | Change characteristics of the equivalent stress and permeability in different areas of gob-side coal seam

Figures 5 and 6 demonstrate the equivalent stress distribution and permeability change of gob-side coal seam along with the inclination. As can be seen from Figure 5, the peak stress is 23 MPa at approximately 11 m distance from the gob edge. The equivalent stress is seen to gradually decrease with increasing distance from the gob and finally recover to the original stress of 13.5 MPa, corresponding to a stress concentration factor of 1.7. Figure 6 demonstrates that the increasing
multiples of permeability dropped from a magnitude of $10^4$ to 1 within the range of 0-9 m inward to the coal body. Under the concentrated stress, the permeability decreases to the lowest value at a distance of 12 m from the coal wall. This is only 0.4% of the initial permeability, and following which it increases slowly.

The variation of equivalent stress and permeability in the gob-side coal body presented the zoning characteristics. After excavation, the gob-side coal seam can be divided into three zones: the rupture penetration, the stress concentration, and the original elastic zones.

1. The rupture penetration zone can be defined as an area 0-9 m away from the gob-edge. In the process of advancing, the abutment stress exceeds the bearing limit of the coal body and the plastic failure occurs. This results in a gas-conducting fracture zone where permeability increases significantly.

![Figure 3](image3.png)

**FIGURE 3** Deformation and damage distribution of the overlying strata: (A) Resultant displacement of overlying strata after the coal seam is mined out; (B) Damage distribution of overburden and coal seam

![Figure 4](image4.png)

**FIGURE 4** Cloud diagram of equivalent stress distribution of coal and rock strata after mining

![Figure 5](image5.png)

**FIGURE 5** Distribution of Von Mises stress
2. The stress concentration area is the region 9-40 m away from the gob-edge. The region contains the elastic-plastic transition interface, with part of the coal body in plastic. The vertical stress upon the panel and the rupture penetration zone will transfer partially to this region due to the destruction of the rupture zone. The coal body in this area is in a compression state and the permeability is less than the initial value, reaching the lowest magnitude at the peak stress point.

3. The original elastic zone is 40 m away from the edge of the gob. In this zone, the stress and the permeability both gradually return with the distance from panel margin. The influence of mining activities on the coal seam in this area is negligible.

### 5.2 Gas pressure measurement results

Twelve boreholes were designed and arranged within 10-25 m of the gob-side coal seam to monitor variations in gas pressure during mining. As the angles between the pressure measurement boreholes and the coal seam were gentle, sealing the boreholes was problematic and some of the boreholes leaked and consequently failed to measure the gas pressure. Only five boreholes, namely M1_1, M1_2, M1_4, M3_1, and M3_4 were operational throughout the measurement period. The pressure varied with the advancing distance of the working face measured by the five boreholes as presented in Figure 7.

As presented in Figure 7, the average gas pressure drop of 10-23 m away from the panel are 1.5 MPa (M1_1 & M3_1), 1.2 MPa (M1_2), and 1 MPa (M1_4 & M1_4), respectively, and the average drop rates are 71%, 46%, and 34%, respectively. The gas pressure of the gob-side coal body is effectively alleviated under the panel-mining disturbance, and the distance between the boreholes and the gob-edge is the main factor affecting the amplitude and duration of the gas pressure drop.

It could be seen that the pressure at each measuring point underwent the process of relief and then stabilization throughout the whole advancement, demonstrating the variation of the pressure that could be grouped into three distinct stages according to the advancing distance:

1. **Initial disturbance stage.** This stage is defined as being within 25 m ahead of the working face along with strike. During this period, the gas pressure at the measuring points increases gently. The original stress of the coal mass ahead of the working face is disturbed by excavation, part of the stress will transfer, leading to the increase in pressure at the boreholes under the coupled effect of the solid-gas fields.

2. **Continuous disturbance stage.** This stage is defined as being within 230 m behind the working face. During the stage, the gas pressure continues to drop after the working face passes through the measuring spots. The coal body near the measurement boreholes is damaged to varying extents with the advancement of the working face, and gas in the coal body will flow out through the fracture network generated.

3. **Stable stage.** In this stage, the working face is advanced beyond 230 m from the monitoring locations. The rate of change of the gas pressure decreases greatly, eventually reaching zero, indicating that gas in the gob-side coal body no longer flows. Two reasons may be responsible for this phenomenon: firstly, gas in the gob-side coal body is exhausted in the continuous stage; secondly, permeability in the measurement location decreases due to the stress action after the mined-out zone of the panel is recompacted.

![Figure 6: Variation of increasing multiple of permeability](image)

![Figure 7: Change curves of gas pressure with the advancement of the working face](image)
5.3 Comparison between the modeling and the field measurement results

Figure 8 demonstrates the comparison between the numerical calculations and the field measurement results of gas pressure at 15 m and 23 m away from the gob-edge over 380 days after mining.

The numerical calculation results are generally consistent with the field measurement data. The behavior of field gas pressure is close to that of the numerical model over the first 300 days. After that, the gas pressure in the field remained stable, while the pressure calculated from the simulation kept decreasing at a slow rate. A reason for the difference might be that the gas diffusion effect of coal is not considered as part of gas seepage during the simulation. After 300 days of the working face advancing (the corresponding distance is 230 m), the gob would be recompacted by falling and bending the rock strata. The stress of coal and rock mass around the gob is stable. However, the gas in the fracture zone was almost exhausted after 300 days of seepage. As a result, the gas in the low permeability zone was likely controlled by diffusion. Based on the consistency of the simulation and the field measurements, the model results are robust to forecast the variation of damage and stress in gob-side coal body.

5.4 Residual gas content investigation results

The average initial gas content of 3603-2 panel was 10.02 m³/t measured before excavation, and the residual gas content after mining is shown in Table 2. The residual gas content within 10-23 m from the panel margin was 2.62-7.36 m³/t, increasing with the distance away from the gob-edge. The decreasing rate of residual gas content is 26.55%-73.58%. It is further indicated that the advancement of the upper working face has a great promoting effect on the gas desorption and release of the lower coal seam.

5.5 Range of gas outburst elimination

After a long period of flow and diffusion, the gas pressure of gob-side coal seam in the field and the numerical simulation were into a stable stage. The distribution of gas pressure and damage in this stage are presented in Figure 9. Figure 9A shows the gas pressure distribution along with the dip in the numerical model, Figure 9B demonstrates the corresponding relationship between the damage and gas pressure in the gob-side coal seam, and the measured gas pressure is shown on it for comparison.

It can be seen from Figure 9B that within the range of 0-5 m the gob-side coal body is almost crushed, and dramatically decreases to zero in the next 8 m. The gas pressure distribution shows a corresponding variation trend. However, the change of gas pressure always lags behind the damage due to the existence of the gas pressure gradient. From Figure 9A,B, the gas pressure is stable at 1 atm in the range of 0-9 m, which is 4 m larger than the area of the completed destruction of the coal body, the near-linear recovery area of gas pressure was also 7 m larger than that of the damage. By comparing the gas pressure in the field with that in the numerical simulation, we can see that the variation of gas pressure is nearly the same, but the measured gas pressure is slightly larger than the numerical simulation within the range of 10-15 m.

According to the regulations relating to the coal and gas OPE in China, the CGO has been eliminated in the coal body as long as the gas pressure (the gas content) is less than 0.74 MPa (8 m³/t). The residual gas content within the range of 23 m meets the requirement of OPE. However, it should be taken into consideration that the gas pressure of the gob-side coal body within the range of 12-23 m in the model is beyond the 0.74 MPa because of the highly concentrated stress. Based on the criterion and the gas pressure results of the numerical simulation, the gas outburst elimination belt is set to be 11.8 m, but given the place 11.8 m away from the panel margin is highly stressed in the numerical study, the range of the belt should be smaller. The field results showed that the drop rate of the gas pressure and content in the coal pillar 10 m away from the gob-side both exceed 70%, and the values of those two meet the requirement of regulations. Therefore, the size of the required gas outburst elimination belt is determined to be 10 m.

6 CONCLUSIONS

The results of the numerical simulation and field measurement showed that the exploitation of the upper section panel promote the gas releasing in the gob-side coal body, and form a gas outburst-proneness elimination (OPE) belt with a certain range. Besides, the simulation was applied to investigate the failure of the overlying strata and the lower gob-side coal body under the mining by taking the characteristics of the constitutive relationship of the weak interlayer into account. Through the field measured data, we concluded the variation law of gas pressure with advancing of the working face. The main conclusions are as follows:

1. After the panel is mined out, the deformation and damaged area of the overlying strata were both trapezoidal in shape, and the stress was concentrated on both sides of the panel where the most severe damage occurred. The lower gob-side coal body can be divided into three
zones according to the changes of the equivalent stress distribution and permeability, namely the fracture penetrating zone, the stress concentration zone, and the original elastic zone. In the fracture penetrating zone, the gas pressure was completely alleviated.

2. The variation of gas pressure with the advancement distance of the working face could be described in three stages: An initial disturbance stage (25 m in front of the working face), a continuous disturbance stage (230 m behind the working face), and a stable stage (more than 230 m behind the working face). Additionally, there was a negative correlation between the distance away from the gob-edge and the gas pressure drop.

3. By comparing the field investigation and the numerical simulation results, it is found that the simulation results were instructive to forecast the range of OPE, combining the results of the field and the modeling results, the width of the gas outburst elimination belt on the gob-side coal seam of the 3603-2 working face in the Hongyan coal mine is 10 m.
As the conclusions of the study show, the advancement of mining face will inevitably cause stress release and gas flow in the gob-side area. Therefore, before designing layout of mining face will inevitably cause stress release and gas flow in the gob-side area. Thus, the stress and gas parameters of the middle zone between the upper and lower section can be tested to determine the pressure relief protection range and reduce the workload of outburst elimination.

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