Study on Gas Emission Characteristics in Lower Stress-relief Coal Seam for Improving Mining Safety of Extremely-close Upper Seam: Implementation of Coupled Permeability Model

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Abstract. In two extremely close coal seams, when the upper coal seam being first mined, large amount of gas normally emits into the mining area from lower stress-relief seam. This is a significant safety issue which may lead to gas-related incidents. In this paper, a coupled permeability model was developed. Then COMSOL Multiphysics numerical simulation was conducted to study multi-factor coupling gas emission flow characteristics. Furthermore, effects of coal stress, gas pressure and initial coal permeability on gas pressure change in lower stress-relief coal seam was analysed. The numerical model established is based on a real case of Ji15 coal seam and Ji16-17 coal seam in Pingdingshan No. 8 coalmine, China. Results show that after upper seam (Ji15 coal seam) being mined, the closer to bottom of working face, the lower the gas pressure because of increasing gas emission performance. As the distance from floor of working face increases, gas pressure becomes closer to its original value. Meanwhile, due to gas emission, gas pressure drop in lower stress-relief coal seam (Ji16-17 coal seam) is symmetrical from the middle of mining face to two ends. Along the parallel direction of mining face, gas pressure curve is approximately in “W”-shape, with gas pressure at both ends tends to be original. From two working face ends to the middle, gas pressure first decreases before increasing, with a maximum decrease of 9.36%. Furthermore, coal stress, gas pressure and initial coal permeability are all positively correlated with gas pressure decrease. Significance of initial coal permeability’s effect is higher than the other two factors. Above results could provide references on drainage borehole design for related scholars and on-site engineers, which is of significance for improving mining safety.

Keywords: Gas emission; Extremely close coal seams; Multi-factor coupling; Mining safety.

1. Introduction
Coal is an indispensable part of China's energy. Thus coal mining safety has been greatly concerned around the country. Gas-related incidents always cause the most serious harm in all kinds of coal mine accidents, accounting for 80% of China's serious coal mine accidents [1]. Therefore, control of gas is of significance for mining safety, in which, borehole gas drainage is one of the most popular methods. Furthermore, in gas drainage practice, it is always adopted to increase the efficiency of gas extraction in one coal seam through first mining its adjacent seam, as the first mining could relieve stress and increase coal permeability in the gas-drainage coal seam [2,3]. However, if the first mined coal seam is extremely close to its neighbouring stress-relief seam. Large amount of gas would emit into first-
mined coal seam from adjacent seam and threat mining safety. Gas emission characteristics are affected by many factors. The study of multi-factor coupled gas emission flow is of great theoretical and practical significance for safe mining.

Factors affecting gas emission flow mainly include gas adsorption and desorption, rock damage, coal stress and permeability anisotropy. Scholars all over the world have achieved fruitful results in the study of gas seepage in coal seams under influence of multiple parameters. Fan Penghong and Nie Baicheng studied the seepage characteristics of coal samples under two mining stresses by means of seepage experiment and theoretical analysis. Finally they obtained permeability variation law [4]. Xie Heping, Zhang Zetian et al studied the effects of mining stress on permeability of mining coal under three mining methods [5]. Shi and Durucan believed that the permeability variation is mainly controlled by horizontal effective stress. Then they introduced cleat compression term and matrix contraction term to reflect impact of horizontal effective stress and pore pressure on seepage characteristics [6]. Based on the linear elastic strain theory, Palmer and Mansoori derive another permeability model under uniaxial strain, which is a function of effective stress and matrix contraction [7]. Tan Yunliang and Yin Yanchun used Lattice Boltzmann method to establish a gas seepage equation considering the adsorption-desorption characteristics and slippage effects, and obtained the influence of gas adsorption, desorption and slippage effects on seepage [8]. Yu Chuxin, Xian Xuefu et al. established the control equation of coal seam gas seepage under the assumption that gas adsorption and desorption process being completely reversible [9]. Rong Tenglong, Zhou Hongwei, etc. theoretically deduced the elastic modulus of coal matrix from perspective of fracture deformation caused by desorption and damage, and introduced the concept of internal expansion strain coefficient. At the same time, based on damage constitutive relationship of Drucker-Prager failure criterion, two permeability evolution models considering coal damage and fracture were established [10]. Tu Min and Fu Baojie conducted permeability experiments on coal samples from stress relief seams affected by mining, and studied the changes in permeability influenced by mining-caused coal and rock damage [11]. Chen Haidong set the unloading mechanics path similar to the stress change of first-mined seam, and carried out permeability test [12]. Xue Yi, Gao Feng et al. took into account impact of excavation damage on coal and rock permeability. They established a post-peak coal and rock permeability model considering damage effect. Finally, they compared experimental test data with the permeability model calculation results, verifying rationality of permeability model [13]. Zang and Wang studied the single-phase gas flow in anisotropic coal by adopting numerical simulation [14]. Liu et al. considered heterogeneous characteristics of cleat compressibility in coal, and developed coal permeability model. But the permeability in each direction is controlled by average effective stress [15]. Gu and Chalaturnyk set discontinuous coal body as an equivalent continuous elastic medium, and established a permeability model that took into consideration changes in mechanical state of coal, adsorption and desorption and anisotropy [16]. Xie Heping established theoretical expression of coal permeability under the coupling effect of pore pressure, support pressure and gas adsorption expansion [17].

Among previous studies, it could be found that related researchers have separately investigated four factors’ effects on permeability change, i.e. gas adsorption and desorption, rock damage, coal stress and permeability anisotropy. However, investigation on those four factors’ coupling effect on permeability is rarely reported [18], which often results in inaccurate research results on gas seepage laws in stress-relief coal seam. At the same time, in Pingdingshan No. 8 Mine of China, Ji15 coal seam and Ji16-17 coal are very close, with the distance only being 4m. When firstly mining the Ji15 coal seam, gas from Ji16-17 coal seam will pour into the goaf of Ji15 coal seam, which could easily cause gas-related accidents. Therefore, a permeability model coupling stress, gas desorption, coal damage and anisotropy are established in this study. Then based on mining condition of Ji15 coal seam of Pingdingshan No. 8 coalmine, numerical simulation model is developed using COMSOL Multiphysics software. Evolution law of coupled gas seepage field in lower stress-relief Ji16-17 coal seam are studied. Results could provide scientific guidance for design of gas drainage drilling in Ji16-17 coal seam, as a result, preventing gas emission from Ji16-17 coal seam into mining area of upper Ji15 coal seam.
2. Theoretical Basis

After the first-mining J115 coal seam being mined, the goaf is formed. Original stress field experiences redistribution, mainly being stress relief. Meanwhile, adsorption balance of gas in coal also changes, which makes gas continuing to desorb and migrate. Gas desorption causes coal matrix shrinkage which could lead to permeability increase. In addition, due to mining disturbance, rock strata around the first mining layer experiences different degrees of damage. Large amount of cracks develop and the permeability rises. As the degree of stress relief in horizontal and vertical directions is different, as well as coal damage. Therefore, mining effects on permeability change in different directions is also different. In order to make numerical results closer to real value, it is urgent to build a permeability model which considers gas adsorption and desorption, rock damage, coal stress and permeability anisotropy.

Permeability is a key factor affecting gas flow. Assuming coal has a typical dual pore structure, and coal permeability is largely dependent on coal cleat. Variation of permeability could be expressed as a cubic function of porosity change [19]:

$$\frac{k}{k_0} = \left(\frac{\Phi}{\Phi_0}\right)^3$$  \hfill (1)

Among them, $k$ is permeability; $k_0$ is the initial permeability; $\Phi$ and $\Phi_0$ is for the porosity and initial porosity of coal, respectively.

The variation of porosity is affected by total equivalent strain variation caused by stress and gas adsorption and desorption:

$$\frac{k_i}{k_{i0}} = \sum_{i\neq j} \left(1 + \frac{3}{\Phi_0}\Delta\varepsilon_{ij}\right)^3$$  \hfill (2)

Among them, $i, j = x, y$ correspond to the vertical and horizontal directions; $k_i$ is the permeability in $i$ direction; $k_{i0}$ is the initial permeability in $i$ direction; $\Delta\varepsilon_{ij}$ is the total equivalent strain variation in $j$ direction.

The total equivalent strain variation can be expressed as:

$$\Delta\varepsilon_{ij} = \Delta\varepsilon_{sij} - \frac{\Delta\varepsilon_{glj}}{3}$$  \hfill (3)

Among them, $\Delta\varepsilon_{sij}$ is the strain change caused by stress variation in $j$ direction, and $\Delta\varepsilon_{glj}$ is the linear strain variation induced by gas adsorption in $j$ direction. $\Delta\varepsilon_{sij}, \Delta\varepsilon_{glj}$ is as follows:

$$\Delta\varepsilon_{sij} = \varepsilon_j - \varepsilon_{j0}$$  \hfill (4)

$$\Delta\varepsilon_{glj} = \varepsilon_L \left(\frac{p}{P_L+p_0} - \frac{p_0}{P_L+p_0}\right)$$  \hfill (5)

Where $\varepsilon_j$ is the strain of coal in $j$ direction; $\varepsilon_{j0}$ is the initial strain of coal in $j$ direction; $\varepsilon_L$ is the Langmuir volumetric strain constant; $P_L$ is the Langmuir pressure constant; $p$ is the pore pressure during gas adsorption; $p_0$ is the initial pore pressure.

Zhu and Wei established a damage-based permeability model based on elastic damage theory. In this model, an exponential term is introduced to the cubic relationship to reflect impact of coal damage on permeability [20]. In this paper, an exponential term is also added to permeability model to represent the permeability of damaged coal, as shown below:

$$\frac{k_i}{k_{i0}} = \sum_{i\neq j} \left(1 + \frac{3}{\Phi_0}\Delta\varepsilon_{ij}\right)^3 \exp(\alpha_k D)$$  \hfill (6)

Among them, $\alpha_k$ represents the damage coefficient which reveals degree of coal damage effect on permeability; $D$ represents the damage variable.

Coal failure includes tensile failure and shear failure. In this paper, first strength theory and Mohr—Coulomb criterion are used to judge whether those two failures occur. When the stress of coal meets
the first strength theory, tensile failure will occur, and when the shear strength meets the Mohr—Coulomb criterion, shear failure will occur:

$$C_1 = \sigma_1 - f_{t0}, C_2 = \sigma_1[(1 + \sin \varphi)/(1 - \sin \varphi)] - \sigma_3 - f_{c0}$$  \hspace{1cm} (7)$$

When $C_1 \geq 0$, it is tensile failure; when $C_2 \geq 0$, it is shear failure; when $C_1, C_2 < 0$, no damage occurs.

Among them, $\sigma_1$ is the maximum principal stress; $\sigma_3$ is the minimum principal stress; $f_{t0}$ is the uniaxial compressive strength; $f_{c0}$ is the uniaxial tensile strength; $\varphi$ is the internal friction angle.

Based on Equations (3), (4), (5), (6), (7), we could obtain:

$$\frac{k_f}{k_{f0}} = \left\{ \begin{array}{ll}
\sum_{i \neq j} \left[ 1 + \frac{3}{\theta_4} \left( \frac{\epsilon_j - \epsilon_{j0}}{p_{i}} - \frac{\epsilon_{j0}}{p_{i} + p_0} \right) \right]^3, & C_1 < 0 \text{ or } C_2 < 0 \\
\sum_{i \neq j} \left[ 1 + \frac{3}{\theta_4} \left( \frac{\epsilon_j - \epsilon_{j0}}{p_{i}} - \frac{\epsilon_{j0}}{p_{i} + p_0} \right) \right]^3 \exp \left[ \alpha_k \left( 1 - \frac{\epsilon_{j0}^2}{\epsilon_1^2} \right) \right], & C_1 \geq 0 \\
\sum_{i \neq j} \left[ 1 + \frac{3}{\theta_4} \left( \frac{\epsilon_j - \epsilon_{j0}}{p_{i}} - \frac{\epsilon_{j0}}{p_{i} + p_0} \right) \right]^3 \exp \left[ \alpha_k \left( 1 - \frac{\epsilon_{j0}^2}{\epsilon_1^2} \right) \right], & C_2 \geq 0
\end{array} \right.$$  \hspace{1cm} (8)$$

Among them, $\epsilon_{t0}$ is the maximum tensile principal strain, and $\epsilon_1$ is the maximum principal strain; $C_1$ and $C_2$ are the indexes for determining whether tensile or shear failure occurs, respectively.

3. Numerical Model Development

3.1. Geometric Model and Boundary Conditions

This numerical model uses Ji15 coal seam of Pingdingshan No. 8 coalmine as research object, based on which, the geometric model is established. The length is 405m while the height is 195m. First-mined coal seam is Ji15 coal seam with a thickness of 3.5m. The length of working face in Ji15 seam is 205m. Ji16-17 coal seam is the lower stress-relief layer with a thickness of 1.9m. The boundary condition of the upper boundary of the model is a uniform load of 18MPa. The other three boundaries are set as fixed constraints. As shown in Figure 1.

3.2. Physical Parameters and Initial Conditions of Coal and Rock

Set the gas pressure in Ji15 coal seam, Ji16-17 coal seam as 1.2MPa. Boundary pressure around the goaf of Ji15 coal seam is set as 0.101MPa (simulated atmospheric pressure). In addition, gas is set to flow between the first mining layer, stress-relief coal seam and rock formations between them. Physical and mechanical parameters of rock mass and coal involved in this model include: density, cohesion, friction angle, Young’s modulus, compressive strength, Poisson’s ratio, and various rock types and layer thickness.
Table 1. Physical parameters of coal and rock strata.

| Rock type          | Density (kg/m³) | Young’s modulus (GPa) | Poisson ratio | Cohesion (MPa) | Friction angle (°) | Compressive strength (MPa) | Gross thickness (m) |
|--------------------|-----------------|-----------------------|---------------|----------------|-------------------|----------------------------|-------------------|
| coarse-grained sandstone | 1900            | 4.80                  | 0.31          | 1.9            | 27                | 34                         | 30.00             |
| sandy mudstone     | 1720            | 3.90                  | 0.32          | 1.8            | 26                | 30                         | 5.00              |
| medium-grained sandstone | 2100           | 8.00                  | 0.31          | 2.1            | 29                | 39                         | 3.28              |
| sandy mudstone     | 1720            | 3.90                  | 0.32          | 1.8            | 26                | 30                         | 10.38             |
| Ji15 coal          | 1250            | 1.30                  | 0.39          | 0.9            | 20                | 16                         | 3.50              |
| Ji16-17 coal       | 1280            | 1.50                  | 0.38          | 1.1            | 21                | 18                         | 1.90              |
| fine-grained sandstone | 2300           | 16.0                  | 0.30          | 3.5            | 31                | 50                         | 5.67              |
| Limestone          | 2650            | 24.0                  | 0.25          | 4.2            | 35                | 63                         | 4.90              |
| argillaceous limestone | 1960           | 4.97                  | 0.31          | 2.0            | 28                | 35                         | 1.50              |
| Limestone          | 2650            | 24.0                  | 0.25          | 4.2            | 35                | 63                         | 123.87            |

4. Simulation Results and Analysis

4.1. Gas Pressure Below the Middle Position of Working Face

After the mining of upper coal seam, underlying coal strata swell, resulting in a bottom heave phenomenon. Coal stress greatly relieves. The rock close to the bottom of first-mined coal seam undergo tensile failure due to pressure relief and expansion. Then many new fractures generate. Gas in stress-relief coal seam becomes easier to flow, emitting out to upper goaf area along the expanded or newly formed cracks. The closer the gas to working face, the faster the emission speed. Gas pressure decreases more.

Figure 2 shows gas pressure characteristics on the pressure evaluation line (green line in the figure) under first mining coal seam. Cloud diagram in this figure reveals damage area. It could be seen that with the increasing distance from floor of first mining coal seam, gas pressure is getting closer to original value (1.2 MPa). As gas in the lower seam continues emitting into upper goaf area, gas pressure gradually decreases. Furthermore, gas pressure in the area closer to floor of first mining decreases faster. As distance from floor of first mining layer increases, the gas pressure changes less, and it almost remains unchanged when the distance being more than 5 m. This is because coal seam closer to first mining area are more affected by mining, as a result, the degree of stress relief becomes higher. Meanwhile, tensile failure condition becomes severe. Thus permeability increases more near first mining area. Meanwhile, during the first 400 hours, gas pressure at each point on gas pressure evaluation line decreases rapidly with time. In the following time, gas pressure decreases more slowly. Due to the close distance between stress-relief coal seam and first-mined coal seam, gas from stress-relief coal seam will continue to flow into the mining goaf. Gas concentration in goaf will increase, which is very easy to cause gas-related incidents. Therefore, gas drainage of stress-relief coal seam is of great necessity.
4.2. Gas Pressure Change in Stress-relief Coal Seam

So as to guide gas drainage borehole layout, it is of great significance to understand the flow of gas in pressure-relief coal seam. During first coal mining, stress field experiences redistribution. The underlying stress-relief coal seam undergoes heave deformation, which leads to well-developed fissures in coal seam. Permeability increases significantly. Gas in underlying coal seam keeps emitting into goaf area. It can be seen from Figure 3 that a pressure evaluation line in stress-relief coal seam is adopted to analyse gas pressure changes. In this figure, the small graph is stress distribution in stress-relief coal seam. This figure indicates that from two working face ends to the middle, gas pressure first decreases before increasing, with a maximum decrease of 9.36%. Along the parallel direction of mining face, gas pressure curve is approximately in "W"-shape, with gas pressure at both ends tends to be original. During first 400 hours, gas pressure of stress-relief coal seam has slightly changed. Later, gas pressure in stress-relief layer has decreased as a whole. Gas pressure experiences the largest decrease in the position around 10m away from two working-face ends. Compared the stress distribution line with pressure change line in Figure 3, it could be seen that the area with greatest degree of stress relief corresponds to biggest gas pressure drop. Because when the degree of stress relief being greatest, stress is more likely to change from compressive stress to tensile stress. Coal cracks expand more, and permeability experiences the biggest increase. Thus gas pressure drops most. Therefore, during mining the Ji15 coal seam, gas drainage is of great necessity in the area about 10m away from two ends to better reduce gas emission. Finally, gas-related incidents could be prevented, making the underground mining activities safer.
4.3. Sensitivity Analysis

In this section, effects of coal stress, original gas pressure and initial coal permeability on gas-pressure decrease in stress-relief coal seam is investigated.

4.3.1. Effect of coal stress on gas pressure drop rate. Related studies have shown that coal stress is closely related to buried depth. As the buried depth increases, stress continues to increase. So as to understand the influence of stress on gas pressure decrease in stress-relief layer more clearly. Stresses of 16MPa, 18MPa and 20MPa are chosen in this study. Figure 4 shows the gas pressure cloud diagram below working face corresponding to different original stresses; Figure 5 indicates gas pressure drop rate in stress-relief coal seam after 1200h of gas emission under different coal stresses. It could be seen from Figure 4 that the closer to first-mined area, the higher the degree of gas pressure reduction. Meanwhile, there are more gas pressure reduction at two working face ends. Since the gas pressure reduction in stress-relief coal seam is not very large, it is difficult to distinguish gas pressure differences corresponding to three stresses only by cloud chart in Figure 4. Therefore, drop rate of gas pressure in stress-relief coal seam are provided in Figure 5. No matter which stress value, the gas pressure drop rate in middle area almost are the same. Gas pressure at two ends of coal seam tends to be original. The area where gas pressure drops the most has the greatest degree of stress relief. The cracks increase the most, and the gas drop has the highest degree. However, because the coal seam at both ends are less affected by mining area. Permeability hardly increases, and gas pressure drops very little. It could be seen from Figure 5 that coal stress is proportional to gas pressure rate in stress-relief coal seam. Because the greater the original stress of coal, the greater the degree of stress relief after first mining activity, as well as the damage to stress-relief coal seam. As a result, permeability increases more corresponding to bigger stress. Gas pressure drop rate becomes larger.

![Figure 4. Gas pressure below the working face corresponding to three stresses.](image)

![Figure 5. Drop rate of gas pressure in stress-relief coal seam under three stresses.](image)

4.3.2. Effect of original gas pressure on pressure drop rate. Gas pressure is one of the most significant indicators of coal and gas outburst. It is connected to gas compression energy in coal which
is a source of power for coal and gas outburst. So as to investigate effect of original gas pressure on pressure drop in stress-relief coal seam. Numerical simulation is conducted by changing original gas pressure. Figure 6 shows gas pressure drop rate in stress-relief coal seam corresponding to original pressures of 0.6 MPa, 1.2 MPa and 1.8 MPa, respectively. During mining activities, pressure change in stress-relief coal seam follows an M-shaped decrease. Pressure drop rate increases first before decrease from two ends to the middle of stress-relief seam. Meanwhile, the gas pressure drop rate is almost the same near the middle working face. For those three pressures, the maximum gas pressure drop rate is approximately 9.6%, and the gas pressure drop rate near two ends of coal seam is very small, only about 0.5%. At the same time, it can be decided that the original gas pressure in stress-relief coal seam is positively correlated with pressure decrease. The greater the original gas pressure, the higher the decrease of stress-relief coal gas pressure. However, the impact of original gas pressure is limited. When the original gas pressure increases to a certain degree, the gas pressure drop rate of stress-relief coal seam will almost keep unchanged.

![Figure 6](image_url)

**Figure 6.** Gas pressure drop rate in stress-relief coal seam under different original gas pressures.

### 4.3.3. Effect of initial coal permeability on gas pressure drop rate.

In the process of CBM engineering, coal permeability is a significant parameter that affects CBM production. Also, during the first coal mining, drop rate of gas pressure in stress-relief coal seam is nearly connected to initial coal permeability. Meanwhile, the initial coal permeability may increase hundreds of times due to coal mining. The greater the initial coal permeability, the higher the increased permeability in stress-relief coal seam. Figure 7 is gas pressure drop in stress-relief coal seam after 1200h of gas emission corresponding to different initial coal permeability. This figure reveals that when the initial coal permeability being $0.8 \times 10^{-14} \text{m}^2$, gas pressure drop rate in stress-relief coal seam is slight. While the initial coal permeability being $1.6 \times 10^{-14} \text{m}^2$, the gas pressure drop rate increases overall. Furthermore, for initial coal permeability of $2.4 \times 10^{-14} \text{m}^2$, most of gas pressure drop rate exceeds 6.3%, and the maximum reaches 17.22%. Therefore, the initial coal permeability is directly proportional to decrease in gas pressure in stress-relief coal seam. Compared with other two elements of coal stress and original gas pressure, the initial coal permeability has a significantly greater influence on drop rate of gas pressure in stress-relief coal seam. Thus, gas emission in stress-relief seam with high permeability should be especially controlled.
5. Conclusions
In this study, following conclusions could be obtained:

(1) In two extremely-close coal seams, during mining the upper seam, the closer to bottom of working face, the lower the gas pressure because of increasing gas emission performance. As the distance from floor of working face increases, gas pressure becomes closer to its original value.

(2) In the stress-relief coal seam, along the parallel direction of mining face, gas pressure curve is approximately in "W"-shape, with gas pressure at both ends tends to be original. From two working face ends to the middle, gas pressure first decreases before increasing, with a maximum decrease of 9.36%. And gas pressure decreases slowly within the first 400 hours, after which, it decreases faster. Meanwhile, gas pressure in the area 10m away from two ends of working face experiences the largest drop rate. Due to the highest degree of damage of coal seam in this area, the permeability has been greatly improved. Thus large amount of gas emit out, resulting in biggest pressure drop rate.

(3) Sensitivity analysis shows that coal stress, original gas pressure and initial coal permeability are all positively correlated with gas pressure drop in stress-relief coal seam, among which, initial coal permeability has the most significant impact than other two factors. Therefore, gas emission in stress-relief seam with high permeability should be particularly controlled.

Results of this study are expected to deliver certain guidance for gas drainage engineering design in stress-relief coal seam, aiming to guarantee the first mining safety.

Acknowledgments
This work is financially supported by National Key R&D Program of China (No. 2018YFC0808000), National Natural Science Foundation of China (Nos. 51904013, 51874009), the Open Research Fund of State Key Laboratory of Coal Resources and Safe Mining, CUMT (No. SKLCRSM20KF003), Anhui University Natural Science Research Project (No. KJ2019A0124), Youth Science and Technology Talents Support Program (2020) by Anhui Association for Science and Technology (No. RCTJ202005).

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