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ABSTRACT: Climate warming has currently been one of the most important global environmental issues. Coal mine methane (CMM) is a typical greenhouse gas with higher global warming potential and ozone depletion potential than CO2. Unfortunately, it should be noted that the CMM emission increases rapidly with the increasing coal consumption in China. Fast and whole protection technology of borehole is a recently developed method to maintain the drainage efficiency in deep mining level. However, the potential negative impact of screen pipes on CMM drainage efficiency has not been well studied. To investigate this impact, an innovative coal permeability model from elastic to post-failure state was deduced to develop our previous gas migration model. Then redistributed stress, coal permeability and gas pressure around a borehole were studied by implementing the mathematical model into Comsol Multiphysics. Numerical results indicate that the negative impact of screen pipes on drainage subpressure do not affect the drainage efficiency due to the stress redistribution. Engineering application shows that comparing to the traditional borehole protection technology, the gas concentration increases about 120% and the gas flux increases about 110% by using the fast and whole protection technology. The research will provide theoretical foundation of CMM capture and borehole protect technology and is of great significance for the CMM utilization and the global environment.

1. INTRODUCTION

Climate warming has currently been one of the most important global environmental issues, which is induced by the increasing greenhouse gasses (CO2, CH4 and N2O) in the atmosphere [1]. For the three main greenhouse gasses, the global warming potential and ozone depletion potential of CH4 are about 23 times and 7 times higher than that of CO2 per unit mass. In China, methane has the second greatest radiative forcing among the long-lived greenhouse gasses after carbon dioxide, accounting for 19.7% of Chinese anthropogenic greenhouse gas emissions [2]. CMM is a general term for all methane released mainly during and after mining operations, accounting for more than half of the nation’s methane released volume [3]. Thus, reducing CMM emission is of vital importance to realize the Paris Climate Agreement of keeping warming well below 2°C [4].

Coal consumption in China is about 4.3 billion tons by 2015 from about 3.1 billion tons in 2010. With China’s rapid economic growth and the growing demand for energy, coal will remain the primary energy source in China in the foreseeable future. However, the mining depth increased rapidly in China as the shallow coal resources gradually exhausted in the past few years. The mining depths of some coal mines in central and east China now reach between 800 m and 1200 m. The deep mining conditions are characterized by high in-situ stress, high methane gas pressure and content, low strength and low permeability [5].

Degassing coal seams with drainage boreholes is an important method to reduce CMM emissions, and results in the beneficial recovery of a clean burning, low-carbon fuel resource. However, the CMM capture (drainage) engineering faces many challenges from the deep mining conditions. Borehole stability problem in-
duced by high in-situ stress and low coal strength is one of the main challenges that influences the CMM capture effectiveness [6–8]. The stability analysis of drainage borehole and protection technology have drawn a lot of attention [9–12], and recently protecting borehole with screen pipes has been developed to solve the stability problem [6]. However, the influence of screen pipes on drainage efficiency has not been well studied, limiting the rational application of the borehole protection technology.

In this study, first, the basic situation of deep coal mine methane in China, and a brief review of the fast and whole borehole protection technology were well illustrated. The possible influence of screen pipes on drainage efficiency was also proposed in this part. Then, a novel coal permeability model from elastic to post-failure state was deduced to develop our previous gas migration model. Finally, the coal permeability model coupling with the gas migration model were implemented into Comsol Multiphysics to study the stress, coal permeability and gas pressure around a borehole. Based on the numerical results, the influence of screen pipes on drainage efficiency was well analyzed, which was also verified by the engineering application. The research will provide theoretical foundation of CMM capture and borehole protection technology and is of great significance for the CMM utilization and the global environment.

2. DEEP COAL MINE METHANE AND BOREHOLE PROTECTION TECHNOLOGY

2.1. Deep Coal Mine Methane

CMM that is emitted from international coal mines represents approximately 8% of the world’s anthropogenic methane emissions contributing 17% to the total anthropogenic greenhouse gas emissions. By 2020, CMM emissions are projected to increase, with estimates as high as 793 MtCO₂e (× 1000 tons CO₂ equivalent) [13]. In China, coal reserve within the burial depth of 2,000 m is about \(5.57 \times 10^{12}\) t, for which is about \(2.86 \times 10^{12}\) t within the burial depth between 1,000 m and 2,000 m, occupied about 51.34% of the total coal reserve [14]. It is well known that gas pressure and gas content increase with the burial depth. The increasing gradient of gas pressure is usually approximate to the hydrostatic pressure gradient, and the increasing gradient of gas content is usually between 1m³/(t·52m) and 1m³/(t·75m). According to the statistical data, the coalbed methane (CBM) reserve is about \(3.68 \times 10^{13}\) m³ when the burial depth is within 2,000 m, and which is about \(2.59 \times 10^{13}\) m³ when the burial depth is between 1,500 m and 2,000 m.

Moreover, the evolutionary trend of the deep CMM also can be inferred from the evolution of CMM drainage quality and utilization quality. The CMM drainage quality and utilization quality from 2005 to 2014 are listed in Table 1. For convenience of discussion, the statistical data is also illustrated in Figure 1. It can be found that the CMM drainage quality is about \(1.7 \times 10^{10}\) m³ by 2014 increases 7.4 times from about \(2.3 \times 10^{9}\) m³ in 2005. At the same time, the CMM utilization quality is about \(7.7 \times 10^9\) m³ by 2014 increases 8.6 times from about \(9.0 \times 10^8\) m³ in 2005. The growth of CMM utilization quality is higher than that of CMM drainage quality. However, the CMM utilization ratio is still lower than 50%, resulting in at most about \(3.0 \times 10^9\) m³ greenhouse gas directly discharges into the atmosphere per year. The low utilization ratio is mainly because the CMM drainage is still with low efficiency induced by borehole instability, sealing performance, etc., and there are still many problems in using low concentration CMM in industry. Thus, increasing the CMM drainage efficiency in deep mining level is of great significance in reducing greenhouse gas emission in the future.

2.2. Fast and Whole Protection Technology of Borehole

Due to high in-situ stress and low strength of surrounding rock, boreholes in the deep level are characterized by weak stability (Figure 2). As borehole drilling can generate great influence on the in-situ stress distribution, a certain range of coal surrounding a borehole will break after excavation, thus causing great diff-

<table>
<thead>
<tr>
<th>Year</th>
<th>CMM Drainage Quality (m³)</th>
<th>CMM Utilization Quality (m³)</th>
<th>Utilization Factor (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>(2.30 \times 10^9)</td>
<td>(9.00 \times 10^8)</td>
<td>39.13</td>
</tr>
<tr>
<td>2006</td>
<td>(3.24 \times 10^9)</td>
<td>(1.15 \times 10^9)</td>
<td>35.49</td>
</tr>
<tr>
<td>2007</td>
<td>(4.40 \times 10^9)</td>
<td>(1.36 \times 10^9)</td>
<td>30.91</td>
</tr>
<tr>
<td>2008</td>
<td>(5.30 \times 10^9)</td>
<td>(1.80 \times 10^9)</td>
<td>33.96</td>
</tr>
<tr>
<td>2009</td>
<td>(7.19 \times 10^9)</td>
<td>(2.60 \times 10^9)</td>
<td>36.16</td>
</tr>
<tr>
<td>2010</td>
<td>(8.80 \times 10^9)</td>
<td>(3.60 \times 10^9)</td>
<td>40.91</td>
</tr>
<tr>
<td>2011</td>
<td>(1.15 \times 10^{10})</td>
<td>(5.30 \times 10^9)</td>
<td>46.09</td>
</tr>
<tr>
<td>2012</td>
<td>(1.41 \times 10^{10})</td>
<td>(5.83 \times 10^9)</td>
<td>41.35</td>
</tr>
<tr>
<td>2013</td>
<td>(1.56 \times 10^{10})</td>
<td>(6.60 \times 10^9)</td>
<td>42.31</td>
</tr>
<tr>
<td>2014</td>
<td>(1.70 \times 10^{10})</td>
<td>(7.70 \times 10^9)</td>
<td>45.29</td>
</tr>
</tbody>
</table>
ficulties in borehole stability control and leaving a very low CMM capture efficiency.

Figure 2 shows the fast and whole protection technology of borehole and the corresponding key equipment which consists of auger stem with a wide blade, openable bit, suspension device and screen pipes. By using the key equipment, the fast and whole protection technology can be completed in much shorter time and with less disturbance on the borehole wall. The basic procedure of the fast and whole protection technology can be divided into 3 steps: (1) After drilling a borehole, leave the auger stems in the borehole to form a stable flow channel, then set the combination of suspension device and screen pipes through the auger stems; (2) Apply an impact force through the combination to the bit to make it open when the combination reaches the top of the auger stems, then the suspension device will work to provide braced force to fix the combination in the borehole; (3) Take out the auger stems one by one from the borehole then seal the borehole.

With this, screen pipes will act as the drainage pass-way of CMM after borehole collapse. However, the screen pipe can only set limited drainage oillets, for instance, only about 20 oillets can set in one screen pipe (1.5 m). Otherwise, it cannot have enough supporting force to act as a flow channel. Thus, the influence of limited drainage oillets on drainage efficiency should be taken into account when using the fast and whole borehole protection technology.

3. COAL PERMEABILITY MODEL FROM ELASTIC TO POST-FAILURE STATE

The influence of screen pipes on drainage efficiency can be analyzed based on the gas pressure distribution around a borehole. Thus, a mathematical model which can evaluate the coal permeability and gas pressure distribution is needed. Underground openings may cause failure when the surrounding stress exceeds the tensile, compressive, or shear strength of the rock formation, whichever is reached first. For a borehole with the failure potential, the surrounding coal is characterized by elastic-plastic secondary stress distribution [15,16]. Thus, the permeability model should be able to describe the permeability evolution at various deformation state. As a novel mathematical model of coupled gas flow and coal deformation with gas diffusion and Klinkenberg effects has been presented in our previous work [17]. In the following section, we will focus on the permeability model from elastic to post-failure state to make a development of the existing model.
As shown in Figure 3, the conceptual permeability model can be obtained based on the typical permeability evolution during the complete stress-strain process of coal, which consists of three parts. For part I, coal is at elastic deformation state, the relationship between permeability and volumetric stress follows an exponential form [18]:

\[ k_1 = k_0 \exp[b_\sigma (\Delta \Theta)] \]  

where \( k_1 \) is the coal permeability at the elastic deformation state. \( k_0 \) is the initial coal permeability. \( b_\sigma \) is the impact factor of coal volumetric stress on permeability. \( \Theta \) is the volumetric stress.

For part II, coal is at plastic deformation state, which is characterized by unstable fractures evolution. The unstable development of fractures leads to a rapid increase in permeability. To describe the fractures unstable evolution, a damage factor is defined as [19]:

\[ \gamma^p = \sqrt{\frac{2}{3}} (\varepsilon_1^p \varepsilon_1^p + \varepsilon_2^p \varepsilon_2^p + \varepsilon_3^p \varepsilon_3^p) \]  

where \( \gamma^p \) is the damage factor of coal. \( \varepsilon_1^p, \varepsilon_2^p \) and \( \varepsilon_3^p \) are principal plastic strains. The permeability increases linearly with the damage factor when coal generates plastic deformation as [20]:

\[ k_2 = \left( 1 + \frac{\gamma^p}{\gamma^p \xi} \right) k_0 \]  

where \( k_2 \) is the coal permeability at the plastic deformation state. \( \gamma^p \xi \) is the transition value of the damage factor from which the residual behavior begins. \( \xi \) is the sudden increase coefficient of permeability.

For part III, coal is at the residual state, and there will be \( \gamma^p = \gamma^p \ast \), thus

\[ k_3 = (1 + \xi) k_0 \]  

where \( k_3 \) is the coal permeability at the residual state.

In summary, coal permeability model from elastic to post-failure state can be expressed as:

\[
\begin{align*}
    k &= \begin{cases} 
    k_0 \exp[b_\sigma (\Delta \Theta)], & 0 \leq \gamma^p < \gamma^p \ast \\
    (1 + \xi) k_0, & \gamma^p \geq \gamma^p \ast 
    \end{cases}
\end{align*}
\]

4. NUMERICAL ANALYSIS OF THE INFLUENCE OF SCREEN PIPES ON DRAINAGE EFFICIENCY

4.1. Numerical Model and Simulation Projects

The permeability and gas pressure distributions were solved by implementing permeability model and gas migration model into COMSOL Multiphysics, which provides a complete and integrated modeling environment for creating, analyzing, and visualizing multiphysics models. The numerical simulations were conducted in the background of Dingji coal mine (Anhui province).

As the engineering scale 3D model is limited by the computing capability of the personal computer, the numerical simulation was divided into two steps. At the first step, the stress and permeability distributions around a borehole were solved using a 3D geometry model. Then, at the second step, the obtained permeability distribution was implemented into an engineering scale 2D geometry model to calculate the gas pressure distribution.

The geometry and boundary conditions of the simulation model are shown in Figure 4. For Step 1, the 3D analyzed zone measures 4 × 2 × 1 m. A methane drainage borehole with a radius of 48 mm is located in the center of the 3D analyzed zone. The borehole wall was applied as a free boundary. The initial displacement in the analyzed zone was zero. For Step 2, the 2D analyzed zone measures 100 m across by 40 m tall. A methane drainage borehole with a length of 80 m is located in the center of the analyzed zone.
length of the sealing part is 10 m. Two monitoring parts were applied to analyze the influence of screen pipes on gas pressure distribution. Monitoring part 1 is without the influence of screen pipes and monitoring part 2 is with the influence of screen pipes. The length of each monitoring part is 2 m. The boundary conditions of flow model were also applied based on the real engineering condition: a constant pressure of 87 kPa was applied to the methane drainage borehole, while no flow conditions were applied to the other boundaries. An initial pressure of 1.2 MPa was applied in the analyzed zone. The influence of screen pipes on drainage efficiency are analyzed by conducting 4 case studies:

- Case A: considering the influences of both stress disturbance and screen pipes;
- Case B: only considering the influence of stress disturbance;
- Case C: only considering the influence of screen pipes;
- Case D: without considering the influences of stress disturbance and screen pipes.

The input parameters used in these simulations are listed in Table 2, most of which were obtained by experiments and engineering background, and the others were chosen from an appropriate range obtained from recently published studies [17].

### 4.2. Stress and Permeability Distribution Around a Borehole

Figure 5 presents the stress distribution around a borehole. Except for the horizontal stress which is parallel to the borehole, both the vertical stress and horizontal stress change with the distance from the borehole wall. The surrounding coal of the borehole is characterized by elastic-plastic secondary stress distribution. The horizontal stress which is the minimum principal stress increases with the distance from the borehole wall and approaches to the initial horizontal stress. The vertical stress which is the maximum principal stress first increases then decreases with the distance from the borehole wall and approaches to the initial vertical stress. The thickness of the surrounding coal with stress disturbance is about 0.27 m, 5.6 times thicker than the borehole radius. Based on the Mohr-Coulomb failure criterion, the relationship between the stress and strain can be described by the following equations:

\[
\sigma_h = \sigma_v + 2\tau \cos\phi + c \sin\phi
\]

\[
\sigma_v = \sigma_h + 2\tau \cos\phi + c \sin\phi
\]

\[
\tau = \frac{1}{2} \left( \sigma_h - \sigma_v \right) \cos\phi
\]

where \(\sigma_h\) and \(\sigma_v\) are the horizontal and vertical stresses, respectively, \(\tau\) is the shear stress, \(c\) is the cohesion, and \(\phi\) is the friction angle of the coal.

### Table 1. Property Parameters Used in the Numerical Simulation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial gas pressure, (p_0)</td>
<td>1.2 MPa</td>
</tr>
<tr>
<td>Langmuir volume constant, (V_L)</td>
<td>2.42 MPa</td>
</tr>
<tr>
<td>Langmuir pressure constant, (P_L)</td>
<td>21.73 m³/t</td>
</tr>
<tr>
<td>Initial Klinkenberg factor, (b)</td>
<td>1.38 × 10⁶ Pa</td>
</tr>
<tr>
<td>Initial permeability, (k_0)</td>
<td>1.875 × 10⁻⁴ mD</td>
</tr>
<tr>
<td>Sorption time, (r)</td>
<td>9.2 d</td>
</tr>
<tr>
<td>Initial porosity of coal matrix, (\phi_{m0})</td>
<td>0.065</td>
</tr>
<tr>
<td>Initial porosity of fractures, (\phi_{f0})</td>
<td>0.013</td>
</tr>
<tr>
<td>Langmuir volumetric strain constant, (\varepsilon_L)</td>
<td>0.012</td>
</tr>
<tr>
<td>Density of coal, (\rho_c)</td>
<td>1200 kg/m³</td>
</tr>
<tr>
<td>Temperature, (T)</td>
<td>293 K</td>
</tr>
<tr>
<td>Young’s modulus of coal, (E)</td>
<td>1200 MPa</td>
</tr>
<tr>
<td>Young’s modulus of coal grains, (E_m)</td>
<td>3600 MPa</td>
</tr>
<tr>
<td>Poisson’s ratio of coal, (v)</td>
<td>0.3</td>
</tr>
<tr>
<td>Cohesion, (c)</td>
<td>0.83 MPa</td>
</tr>
<tr>
<td>Friction angle of coal, (\varphi)</td>
<td>35°</td>
</tr>
<tr>
<td>Impact factor of volume stress to permeability, (b_0)</td>
<td>0.05 MPa⁻¹</td>
</tr>
<tr>
<td>Transition value of the damage factor, (\gamma^*)</td>
<td>0.003</td>
</tr>
<tr>
<td>Sudden increase coefficient of permeability, (\zeta)</td>
<td>20</td>
</tr>
<tr>
<td>Horizontal stress, (\sigma_h)</td>
<td>16 MPa</td>
</tr>
<tr>
<td>Vertical stress, (\sigma_v)</td>
<td>20 MPa</td>
</tr>
</tbody>
</table>
Coulomb criterion which is the most commonly used failure criterion, the surrounding coal within the stress disturbance zone can be divided into plastic deformation zone and elastic deformation zone. The plastic deformation zone is from the borehole wall to the boundary where the vertical stress reaches the maximum value (33 MPa), whose thickness is about 39 mm. The elastic deformation zone covers the other stress disturbance zone.

Figure 6 presents the relative coal permeability distribution around a borehole. It can be found that the coal permeability first decreases then increases with the distance from the borehole wall, and approaches to the initial coal permeability. The maximum coal permeability is about 1650 times higher than the initial permeability, and the minimum one is about 0.5 times lower than the initial permeability. The thickness of the permeability increased zone is approximately 40mm, which is almost equal to the thickness of the plastic deformation zone, indicating that the fractures in the plastic deformation zone are fully extended, generated and connected. However, due to the vertical stress concentration, the permeability is lower than the initial value in the elastic deformation zone. Beyond the stress disturbance zone around the borehole, the coal permeability remains unchanged.

4.3. Discussion of the Influence of Screen Pipes on Drainage Efficiency Based on the Gas Pressure Distribution

Figure 7 presents the gas pressure distributions with different drainage times. The minimum and maximum values of the analyzed are 87 kPa and 1.2 MPa, respectively. The low gas pressures zones are directly sur-
rounding the drainage borehole and along the roadway, induced by the in-situ stress and permeability redistribution. At the same time, it is clear that the proportion of the low gas pressures zones increases with the increasing drainage time. However, the maximum pressure remains at the initial value of 1.2 MPa beyond the low gas pressure zone, indicating that a single drainage borehole exhibits only limited effects. Moreover, as illustrated in Figure 7, there is an abnormal pressure area obtained without considering the influence of stress disturbance, in which the gas pressure is higher than the close region. More details about the abnormal pressure area and gas pressure distribution will be discussed by extracting the pressure data along the detection line. The detection line is located at the center of the abnormal pressure area, which is split into two parts by the drainage borehole. The length of each part of the detection line is 8 m.

Figure 8 shows the gas pressures along the detection line under different case conditions. It is clear that the gas pressure decreases with the drainage time for all case conditions. When considering the influence of stress redistribution (i.e. permeability redistribution), it is very difficult to recognize the gas pressure difference between case A and case B, i.e. screen pipes generated negligible influence on gas drainage efficiency. However, without considering the influence of stress redistribution, significant difference of gas pressure between

![Figure 7. Gas pressure distributions in the coal seam around a drainage borehole at different times.](image)

![Figure 8. Gas pressure distributions along the detection line at different times.](image)
case C and case D can be found. The gas pressure with considering the influence of screen pipes is higher than that without considering their influence. Thus, it can be concluded that the limited drainage oillets will have a negative impact on drainage subpressure when using screen pipes.

As discussed in Section 4.2, it is clear that there is a high permeability zone around a borehole when considering the stress redistribution. Coal permeability is usually recognized as the most important factor that controls the gas migration in a coal seam. The high permeability zone around a borehole (as discussed in Section 4.2) can balance out the negative impact of screen pipes on gas pressure evolution. Otherwise, if there is no high permeability zone, the negative impact of screen pipes will influence the gas pressure evolution. Thus, from the numerical results, we inferred that, with the influence of stress redistribution, the negative impact of screen pipes on drainage subpressure would not influence the drainage efficiency.

5. ENGINEERING APPLICATION

In the following section, comparisons of production between two groups of drainage boreholes at the No.1331 working face (Dingji coal mine) have been made. The depth of the No.1331 working face is between 780 m and 870 m. The length and width of the No.1331 working face are about 1420 m and 210 m, respectively. The coal seam of the No.1331 working face is characterized by very low strength, whose Platts hardness coefficient is only 0.6. The average thickness and inclination angle of the coal seam is approximately 1.8 m and 3°, respectively. The gas content and gas pressures are 5.6 m³/t and 1.2 MPa, respectively.

For comparison, 60 drainage boreholes with lengths of approximately 110 m have been chosen and divided into two groups. Screen pipes have been installed in these boreholes with two different methods, as these boreholes have quite low stability. The screen pipes will act as a methane flow channel when the failure of the borehole occurs. The traditional method was used to install screen pipes in the boreholes of the group 1, with only 60% percent of the length of these boreholes being supported by screen pipes, while nearly 100% percent the length of the boreholes of group 2 was supported by screen pipes with the fast and whole protection method.

As shown in Figure 9, both the concentration and flux of group 2 are much larger than that of group 1. After drainage 25 days, the gas concentration and flux of group 1 are still higher than 33% and 4.2 m³/min, respectively. However, gas concentration and flux of the boreholes of group 2 are lower than 15%, and 2.0 m³/min, respectively. By using the fast and whole protection technology of borehole, the gas concentration increases about 120% and the gas flux increases about 110%, indicating that fast and whole protection technology has a greatly positive impact on CMM drainage efficiency. Accordingly, with the increasing of CMM utilization quality and utilization factor, the amount of CMM emission reduces simultaneously, benefiting the global environment.

6. CONCLUSIONS

Climate warming has currently been one of the most important global environmental issues. CMM (CH₄) is a typical greenhouse gas whose global warming potential and ozone depletion potential are about 23 times and 7 times higher than that of CO₂ per unit mass. Unfortunately, it should be noted that the CMM emission increases rapidly with coal consumption in China. Degassing coal seams with drainage boreholes is an important method to control CMM emission, however, which now faces many challenges induced by the wicked deep mining conditions.

Fast and whole protection technology of borehole is a recently developed method to maintain the drainage efficiency in deep mining level. To explore the insights of the borehole protection technology, the influence of screen pipes on drainage efficiency was discussed by deducing a novel coal permeability model from elastic to post-failure state. Then, the coal permeability model coupling with the gas migration model were implemented into Comsol Multiphysics to study the stress,
coal permeability and gas pressure around a borehole. Numerical results indicate that the negative impact of screen pipes on drainage subpressure do not affect the drainage efficiency due to the stress redistribution. The numerical achievements were verified by the engineering application of the borehole protection technology in Dingji coal mine. Engineering application shows that the gas concentration increases about 120%, and the gas flux increases about 110% by using the fast and whole protection technology of borehole. The research will provide theoretical foundation of CMM capture and borehole protection technology and is of great significance for the CMM utilization and the global environment.

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8. REFERENCES