Numerical simulation of borehole wall remodel during gas drainage

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Abstract. Gas drainage bearing coal and rock mass can be simplified as isotropic homogeneous body with gas saturation. Numerical method was used to study the influence of borehole wall remodel-size, remodel-length and negative pressure on gas drainage effect which based on gas diffusion and seepage equation of pore fracture system and governing equation of coal and rock mass degeneration. The results showed that borehole wall remodel can maintain the support of coal skeleton in borehole and prevent blocking the gas flow channel, gas pressure drop in remodelled section is more obvious than that in the non-remodelled section, the longer the remodelled length of borehole wall the more smooth the gas flow channel between borehole and coal body around borehole, with the increase of negative pressure, the decrease range of gas pressure at the same depth increases, but the difference is small under different negative pressure. On the premise of preventing borehole creep instability, borehole wall remodel can provide high-quality gas flow channel for coal seam gas drainage, maintain the continuous influence of negative pressure on coal body along borehole depth to extend the life cycle of gas drainage and is not sensitive to borehole wall remodel size and negative pressure.

1. Introduction

With the development and exploitation of the mine extending to the deep, it is difficult to predict and control the deep coal mining disasters due to the natural attributes of the occurrence environment of "high ground stress, high gas pressure, high gas content and low permeability" of deep coal and rock mass as well as the additional attributes of "strong disturbance" and "strong timeliness" of deep mining[1]. Gas drainage is the fundamental technical means of mine gas control, However, under the evolution of complex geological conditions, the soft fracture area, fault fracture zone and coal thickness mutation area have difficulties in drilling, serious borehole collapse damage and poor hole wall stability which seriously affect the gas drainage effect[2].

Gas drainage borehole can be regarded as a kind of free space formed by external force in coal and rock mass and extends around it[3-4].The size effect of pressure relief at the initial stage of drilling can be benefit for gas drainage, but the stability of drilling can be affected by the comprehensive factors such as in-situ stress, drainage negative pressure, gas flow, coal and rock mass structure. As time goes on, creep instability will occur when the tensile strain of coal body in the direction of borehole exposed
surface is greater than that of coal body failure\textsuperscript{5-6}. Borehole wall remodel is an effective way to extend the life cycle of borehole during gas drainage, based on previous studies, gas drainage bearing coal and rock mass can be simplified as isotropic homogeneous body with gas saturation. Numerical method was used to study the influence of borehole wall remodel-size, remodel-length and negative pressure on gas drainage effect which based on gas diffusion and seepage equation of pore fracture system and governing equation of coal and rock mass degeneration.

2. Numerical model and solution of borehole wall remodel

2.1. Construction of numerical model

Through establish coal gas solid gas coupling model, the coupling model is discretized by finite difference method and solved by FORTRAN language to analysis the influence of borehole wall remodel size, remodel length and different negative pressure on gas drainage effect.

2.1.1. Gas seepage equation of fracture system

According to the mass conservation of the free gas in the fracture system, the mass of the flowing micro element in each direction per unit time minus the mass of the flowing micro element, plus the mass of the gas desorbed by the micro element pore system is equal to the change of the micro element mass per unit time, so that the gas seepage equation of fracture system can be obtained\textsuperscript{7}.

\[
\frac{\partial}{\partial t} \rho + \nabla \cdot (\rho \mathbf{Q}) = q + \sum_{j=1}^{N} \rho \cdot q' \cdot \delta(x - x_j') \cdot \delta(y - y_j') \cdot \delta(z - z_j')
\]

Where \( \rho \) is the density of free gas, kg/m\(^3\); \( n \) is micro element porosity, coupling solution of gas pressure field and deformation field; \( Q \) is velocity vector of gas seepage, m/s; \( q \) is gas desorption quality of microelements (quality source), kg/(m\(^3\)·s); \( (x_j', y_j', z_j') \) is coordinates of number \( j \) extraction borehole; \( N \) is number of boreholes; \( \delta(x) \) is Dirac delta function; \( q' \) is gas flow of number \( j \) drainage hole, m\(^3\)/s.

2.1.2. Gas diffusion equation of pore system

It is the same micro element as the fracture system, the gas diffusion equation of pore system can be obtained according to the mass conservation of adsorbed gas.

\[
\frac{\partial C}{\partial t} + \nabla \cdot m = -q
\]

Where \( C \) is Gas adsorption quality of unit volume coal seam, kg/m\(^3\); \( m \) is velocity vector of adsorbed gas mass diffusion, kg/(m\(^2\)·s).

The seepage velocity of free gas and diffusion velocity of adsorbed gas are calculated by Darcy's law and Fick's law respectively, the calculation equation of adsorbed gas concentration can be obtained according to Langmuir formula.

\[
\begin{align*}
V &= -\frac{k}{\mu} \nabla p \\
m &= -D \nabla C \\
C &= \frac{abcP_0P_a}{(1 + bP_1) \cdot RT}
\end{align*}
\]

Where \( a \) is limit adsorption capacity of fuel per unit mass, m\(^3\)/kg; \( b \) is adsorption constant, MPa\(^{-1}\); \( c \) is combustible mass per unit volume, kg/m\(^3\); \( P_0 \) is reference pressure, 0.10MPa; \( P_1 \) is adsorption equilibrium pressure of pore system, MPa; \( R \) is gas constant, \( J/(kg \cdot k) \); \( T \) is coal seam temperature, K; \( k \) is permeability of fracture system, m\(^2\); \( \mu \) is gas viscosity, Pa·s; \( D \) is gas diffusion coefficient of pore system, m\(^2\)/s; \( P \) is coal seam gas pressure, MPa.
2.1.3. Deformation control equation of coal and rock mass

It is the same micro element as the fracture system, the governing equations of coal and rock mass deformation can be obtained according to the equilibrium relations of forces in X, Y and Z directions. Taking Z direction as the vertical direction, the differential equation of deformation field with displacement as variable can be obtained according to Hooke's law, coal and rock deformation geometric equation and modified Terzaghi effective stress into deformation control equations [8-11].

\[
\begin{align*}
\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} + f_x &= 0 \\
\frac{\partial \sigma_y}{\partial y} + \frac{\partial \tau_{yx}}{\partial x} + \frac{\partial \tau_{yz}}{\partial z} + f_y &= 0 \\
\frac{\partial \sigma_z}{\partial z} + \frac{\partial \tau_{zx}}{\partial x} + \frac{\partial \tau_{zy}}{\partial y} + f_z &= 0
\end{align*}
\]

(4)

\[
\begin{align*}
E_s \frac{\partial^2 u}{\partial x^2} + G \left( \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) + (G + \lambda) \left( \frac{\partial^2 v}{\partial x \partial y} + \frac{\partial^2 w}{\partial x \partial z} \right) - \frac{\partial (\alpha p)}{\partial x} &= 0 \\
E_s \frac{\partial^2 v}{\partial y^2} + G \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial z^2} \right) + (G + \lambda) \left( \frac{\partial^2 u}{\partial y \partial x} + \frac{\partial^2 w}{\partial y \partial z} \right) - \frac{\partial (\alpha p)}{\partial y} &= 0 \\
E_s \frac{\partial^2 w}{\partial z^2} + G \left( \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} \right) + (G + \lambda) \left( \frac{\partial^2 u}{\partial z \partial x} + \frac{\partial^2 v}{\partial z \partial y} \right) - \frac{\partial (\alpha p)}{\partial z} + \rho_v g &= 0
\end{align*}
\]

(5)

Where \( f_x, f_y, f_z \) are volume forces in X, Y and Z directions, Pa; \( \sigma_x, \sigma_y, \sigma_z \) are normal stress in X, Y and Z directions, Pa; \( \tau_{xy}, \tau_{yx}, \tau_{yz}, \tau_{zy}, \tau_{zx}, \tau_{xz} \) are the shear stress of microelements, \( \tau_{xx} = \tau_{yy}, \tau_{zx} = \tau_{zy}, \tau_{xz} = \tau_{zx} \), Pa; \( G \) is shear modulus, \( G = \frac{E}{2(1+\mu)} \), Pa; \( E_s \) is confined compression modulus, \( E_s = \frac{E(1-\mu)}{(1-2\mu)(1+\mu)} \), Pa; \( \lambda \) is lame constant, \( \lambda = \frac{E\mu}{(1-2\mu)(1+\mu)} \), Pa; \( a \) is Biot value; \( \mu \) is Poisson's ratio; \( E \) is elastic modulus, Pa; \( u, v, w \) are the displacement components in X, Y and Z directions, m; \( \rho_v \) is density, kg/m³.

Considering the influence of pore pressure on coal skeleton, according to the definition of porosity and permeability is a function of porosity, Carman Kozeny formula was used to solve the problem [12-13].

\[
\begin{align*}
n &= 1 - \left( \frac{1-n_0}{1+\varepsilon_v} \right) \left( 1 - \frac{p - p_0}{k_i} \right) \\
k &= \left[ \frac{k_0}{1+\varepsilon_v} + \frac{(p - p_0) \cdot (1-n_0)}{n_0 \cdot k_i} \right]^3
\end{align*}
\]

(6)

Where \( \varepsilon_v = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \) is Volume strain; \( k_i \) is matrix modulus of coal and rock, Pa; \( n_0 \) is initial porosity; \( P_0 \) is initial gas pressure, MPa; \( K_0 \) is initial gas permeability.

2.2. Parameter configuration of borehole wall remodeling model

In order to obtain the simulation effect accurately and guide a better field, the model was established based on the actual situation with dimension parameter of 40m×140m in which the drilling length is 120m and the sealing length is 20m (Figure 1).

The influence of strong disturbance and stress concentration in drilling construction will destroy coal and rock to a certain extent, it is difficult to describe permeability accurately by mathematical model, through the simulation of borehole gas drainage volume, effective radius and field comparison to inversion permeability. Considering the distribution of pressure relief around the borehole, the pressure and permeability are exponentially distributed in the range of 1m on both sides of the borehole\cite{14} (Figure 2).

\begin{align}
    p_{x, y} &= -0.9876 / \exp(\sqrt{x/0.4819}) + 1.6069 (0 \leq x \leq 1) \\
    K_{x, y} &= 1175.03 / \exp(\sqrt{x/0.1450}) + 8.5706 (0 \leq x \leq 1)
\end{align}

According to whether the hole wall is remodelled or not, the boundary conditions of the borehole can be divided into two cases: If remodelled, the boundary around the hole adopts constant pressure, function relationship between pressure in hole and along hole depth can be obtained by simulation; If not remodelled, the gas extraction chamber is regarded as a porous medium with greater permeability than coal, the sealing position set as the pressure outlet boundary and the pressure is equal to the negative pressure of drilling.

\begin{align}
    p_{(x, y)} &= f_{(x, y)} (20 \leq x \leq 20.10) \\
    p_{(x, L)} &= P_c (20 \leq x \leq 20.10)
\end{align}
Where $y$ is the depth of hole, m; $P_c$ is negative pressure of gas drainage, kPa.

It is assumed that the model is surrounded by an absolute current boundary:

$$
\begin{align*}
\frac{\partial p}{\partial x} &= 0, \quad (x = 0, \quad x = 40) \\
\frac{\partial p}{\partial y} &= 0, \quad (y = 0, \quad y = 140)
\end{align*}
$$

(9)

Table 1  Basic parameters of numerical simulation.

| Parameter            | Unit of measurement | Numerical value |
|----------------------|---------------------|-----------------|
| Initial gas pressure | MPa                 | 1.50            |
| Adsorption constant/a| m³/t                | 22.8180         |
| Adsorption constant/b| MPa⁻¹               | 0.9720          |
| Ash content          | %                   | 11.73           |
| Water content        | %                   | 1.38            |
| Apparent density     | kg/m³               | 1.31            |
| Elastic modulus      | Pa                  | 3×10⁹           |
| Poisson's ratio      | --                  | 0.40            |
| Diffusion coefficient| m²/s                | 6×10⁻¹²         |
| Initial porosity     | %                   | 2.24            |
| Initial permeability | m²                  | 9×10⁻¹⁷         |

3. Borehole wall remodel size on gas drainage effect

Under the premise of whether the hole wall is remodelled and remodel size 32, 40, 50mm to analysis extraction effect, for quantitative research, the drilling diameter is 113mm, the drilling length is 120m, the sealing length is 20m, the remodel length is 100m and the negative pressure is 13kPa. Firstly, the gas pressure inside the borehole is simulated according to the remodel size and then the influence of the remodel size on the extraction effect is numerically simulated, The gas pressure cloud atlas was extracted when the drainage time was 30 days and the variation of gas pressure under different remodel sizes was compared and analysed (Figure 3, 4).
1- Not remodelled; 2-remodel size 32mm; 3-remodel size 40mm; 4-remodel size 50mm

Figure 4 Gas pressure cloud atlas around borehole with different remodel sizes

The influence range of gas drainage and gas pressure drop range are obviously different from boreholes whether borehole wall remodelled. Due to the action of ground pressure, the borehole wall collapses and gas extraction chamber compacted when borehole wall not remodelled, only in the area near the orifice appearance the influence range of water drop and the downward trend of gas pressure appear. When borehole wall remodelled, a certain symmetrical area around borehole in the influence range of drainage and gas pressure decreases obviously, but gas pressure drop range decreases with the increase of drilling depth under the action of resistance along the way. Larger remodel size with greater drainage effect along the depth of the borehole, but the overall difference of gas pressure drop along the longitudinal direction of borehole is small and which is approximately ellipsoid shape. In order to compare the gas pressure changes under different borehole wall remodel sizes more intuitively, gas pressure data of borehole sections (x = 2m) and (y = 30m) were extracted and the curves are drawn for analysis (Figure 5, 6).

Figure 5 Influence of borehole wall remodel size on gas drainage effect (x=2m, y=30m)
When the borehole wall is not remodelled gas pressure from the sealing section to the bottom of borehole increases with logistic function gradually increases from 0.81MPa to 1.40MPa and tends to be flat. When the borehole wall is remodelled gas pressure along the drilling depth is basically 0.50-0.70MPa and the pressure drop advantage is obvious. Taking the pressure distribution at the depth of 30, 60 and 90m for example, When the remodelled size is 32mm the gas pressure is 0.53, 0.60, 0.67MPa respectively, When the remodelled size is 40mm the gas pressure is 0.52, 0.57, 0.61MPa respectively, When the remodelled size is 50mm the gas pressure is 0.52, 0.55, 0.57MPa respectively. Larger the remodel size and smaller the gas pressure at the same drilling depth but the overall trend and the influence difference between each other are relatively small.

The large, medium and small sizes (roadway→gas drainage borehole→hole fissure) contained in underground space engineering structure can be regarded as free space of different scales, after the coal and rock in the hole drilling out, the pressure relief of coal body is formed. The main purpose of hole wall remodel is to maintain the coal skeleton support in the borehole and prevent blocking the gas flow channel[4, 15]. Larger remodel size caused larger coal exposed area and more conducive to gas drainage, but at the same time, the length of remodel is difficult to in place and the cost is relatively high. The key impact of remodel size on gas drainage effect lies in whether the borehole wall is remodelled, so remodel size of 32mm is the first choice.

4. Influence of hole wall remodel length on gas drainage effect

Under the premise of determining the remodel size of hole wall to analysis gas drainage effect when remodel length is 40, 60, 80 and 100m, for quantitative research, the drilling diameter is 113mm, the drilling length is 120m, the sealing length is 20m, the negative pressure is 13kPa and the remodel size 32mm. According to the gas pressure in the borehole with remodel size of 32mm, the influence of remodel length on extraction effect is numerically simulated. The gas pressure cloud atlas was extracted when the drainage time was 30 days and the variation of gas pressure under different remodel length was compared and analysed (Figure 7).
Gas pressure distribution around borehole is obviously different under different remodel length, larger influence range of drainage along the depth of borehole and more obvious gas pressure reduction with the increase of remodel length which is consistent with previous studies\(^{[16]}\). Under the effect of gas pressure gradient and negative pressure, the surrounding coal gas flows downstream to the remodelled section of borehole wall which promotes the direction and length of gas seepage path around the borehole to be more conducive to gas drainage. In order to compare the gas pressure changes under different hole-wall remodel length more intuitively, gas pressure data of borehole sections (\(x = 2m\)) was extracted and the curves are drawn for analysis (Figure 8).

Boreholes with different wall remodel length presents a consistent change, gas pressure decreases slowly from the borehole depth of 20m to the starting point of hole wall remodel and the closer to the starting point of hole wall remodel the more obvious for the gas pressure decreases which showed that larger remodel length with better drainage effect. Remodel length will directly affect the effect of negative pressure during drilling process when the drilling depth fixed, the premise of gas drainage is to keep gas flow channel smoothly between borehole and the coal body around it, so the whole hole section should be selected for hole wall remodel in order to give full play to the effect of hole gas drainage.
5. Influence of negative pressure on gas drainage effect
Under the premise of determining the remodelled size and length of borehole wall to analysis gas drainage effect when negative pressure is 13, 20, 30, 40kPa, for quantitative research, the drilling diameter is 113mm, the drilling length is 120m, the sealing length is 20m, the remodel size 32mm and the remodel length is 100m. According to the simulation of gas pressure distribution in hole based on different negative pressure, the influence of negative pressure on gas drainage effect is numerically simulated. The gas pressure cloud atlas was extracted when the drainage time was 30 days and the variation of gas pressure under different remodel length was compared and analysed (Figure 9, 10).

![Gas pressure distribution curve under different negative pressure](image1)

**Figure 9** Gas pressure distribution curve under different negative pressure

![Gas pressure cloud atlas around borehole under different negative pressure](image2)

**Figure 10** Gas pressure cloud atlas around borehole under different negative pressure

Effectives for gas drainage are basically the same under different negative pressure, the main performance is that gas pressure in the area which near the orifice and the borehole wall decreases greatly, but gas pressure decreases gradually with the increase of the distance from the orifice and the wall of borehole. In order to compare the gas pressure changes under different negative pressure more intuitively, gas pressure data of borehole sections (x = 2m) and (y = 30m) were extracted and the curves was drawn for analysis (Figure 11).
Figure 11 Influence of different negative pressure on gas drainage effect (x=2m, y=30m)

The decrease of gas pressure in the same borehole depth increases with the increase of negative pressure but the increase range is relatively small which is consistent with previous studies\(^{[17]}\). However, the increase of negative pressure in limited range has little effect on gas drainage effect does not mean that the influence of negative pressure on gas drainage effect is not important. Higher the negative pressure with higher the requirement of equipment and more severe the quality of borehole sealing, It is necessary to investigate the reasonable negative pressure to ensure gas drainage effect. Based on the comprehensive quantitative analysis and combined with the on-site and reasonable economic demand negative pressure of 13kPa should be selected.

6. Conclusions
1. Larger remodel size caused larger coal exposed area and more conductive to gas drainage, but the length of remodel is difficult to in place and the cost is relatively high. The key impact of remodel size on gas drainage effect lies in whether the borehole wall is remodelled.
2. Remodel length will directly affect the effect of negative pressure during drilling process when the drilling depth fixed, the premise of gas drainage is to keep gas flow channel smoothly between borehole and the coal body around it, so the whole hole section should be selected for hole wall remodel in order to give full play to the effect of hole gas drainage.
3. The decrease of gas pressure in the same borehole depth increases with the increase of negative pressure but the increase range is relatively small, it is necessary to investigate the reasonable negative pressure to ensure gas drainage effect.
4. On the premise of preventing borehole creep instability, hole wall remodel can provide high-quality gas flow channel for coal seam gas drainage, maintain the continuous influence of negative pressure on coal body along the borehole depth to extend the life cycle of borehole gas drainage and is not sensitive to borehole wall remodel size and negative pressure.

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