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Numerical simulation of gas migration tule in mining-induced fractures field

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ABSTRACT
Gas extraction practice has proven that the vast majority of mining areas in China use unfavourable gas drainage technology, such as ground drilling hole, and should instead use mining-induced fractures for gas extraction. Therefore, research concerning the gas migration rule in mining-induced fractures field above the goaf can provide technical support for optimizing system arrangement of pressure-relieved gas extraction, and increasing the rate of gas extraction.

At present, scholars are utilizing numerical simulation to study the gas migration rule in working face and goaf without considering the influence of the mining-induced fractures. There is currently no simulation software that can simulate not only the space-time evolution of the mining-induced fractures field, but also the rule of gas migration. This study takes the mining face of the 10th mine in Pingdingshan Coalmine Group in Henan China as an example case. First, a numerical calculation model is established, and then UDEC software is used to calculate the evolution formation of the mining-induced fracture field. Afterwards, a spatial diagram is obtained by the image processing method, and then imported into COMSOL MULTIPHYSICS software in order to simulate the process of gas migration.

By combining the UDCE and COMSOL software, the gas migration rule in mining-induced fractures above goaf is numerically simulated. The results are as follows: When the working face advances to a certain distance, goaf overburden gradually forms a mining-induced fractures trapezoid table, and with the working face advancing, the height of the mining-induced fractures trapezoid table increases; Compared to the gas migration in the overburden matrix, the gas flow in abscission layer crack and vertical fracture of mining-induced fractures is directional, and the gas enrichment area is located in the biggest abscission layer crack area in upper end of mining-induced fractures trapezoid table; When drilling for gas extraction in mining-induced fracture field, the gas concentration declines in the whole region during the process of gas drainage, and the rate of gas concentration declines faster in fractured zones. With the gas drainage, the velocity of the gas flow in the mining-induced fracture is faster.

1. INTRODUCTION

The geological conditions of coal seams in China are complex and permeability is generally low. Gas extraction practices has proven that the vast majority of the mining areas in China use unfavourable gas drainage technology, such as ground drilling hole. Mining-induced fractures should instead be used for gas extraction. In the process of coal mining, the surrounding rock stress is redistributed and generates the mining-induced fractures caused by mining stope. The gas desorption of coal mass is promoted, and the permeability of coal is also increased in order to provide a gas flow channel in coal and rock mass near the working face. Therefore, research concerning the gas migration rule in mining-induced fractures field above the goaf can provide technical support for optimizing system arrangement of pressure-relieved gas extraction, and increasing the rate of gas extraction.

At present, scholars have carried plenty of research on the gas migration law in mining-induced fracture field above goaf. Qian and Xu (1998) studied the distribution characteristics of mining-induced fractures in the overlaying strata by means of model experiments, image analysis, and discrete element simulation method. Their findings revealed a two stage development law of fracture caused by mining and distribution characteristics of “O-shape” circle in long wall faces, and a guide for hole patterns of relieving gas drainage. Li (1998) classified the mining induced fracture field through research on the formation and characteristics of fracture fields above the goaf and in front of the working face. Tu and Liu (2002) researched the influence of formation, development, closure, and variation of the cracks in the roof of a coal seam on coal mining, and described the range of fracture development. Liu et al. (2012) found that according to the breakage and fracture developing of overlying strata, the layer with a

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fracture diameter of more than 10^{-1} mm is the mining gas channels development area. Other scholars have studied the gas migration law of coal seams using the numerical simulation method. However, no simulation software has been developed that can simulate not only the space-time evolution of the mining-induced fractures field, but also the rule of gas migration.

This study takes the mining face of the 10th mine in Pingdingshan Coalmine Group in Henan China as an example case. Establishing numerical calculation model according to the different laws of gas flow in different zones of the working face, and combining the UDCE and COMSOL software to research the gas migration rule in mining-induced fractures above goaf, which can provide technical support for optimizing the system arrangement of pressure-relieved gas extraction.

2. MATHEMATICAL MODEL OF GAS MIGRATION UNDER THE MINING INFLUENCE

Mining fissure fields belongs to a porous medium and the gas therein can be regarded as the ideal gas mixture consisting of gas and air. The gas flow follows the continuity equation, momentum equation, and mass conservation equation.

2.1 Continuity equation

The gas flow in coal and rock follows the law of mass conservation. If the mass sources (sink) are not considered, the gas continuity equation is:

$$\frac{\partial\left(\rho_g \phi\right)}{\partial t}+\nabla \cdot\left(\rho_g \phi \mathbf{v}_g\right)=0 \quad (1)$$

The gas transportation in mining fissures should satisfy the law of conservation of the gas quality. It should consider the mass sources of gas, so the gas continuity equation is:

$$\frac{\partial(\rho_g c_g)}{\partial t}+\frac{\partial}{\partial x_i}(\rho_g c_g u_i)=-\frac{\partial}{\partial x_i}(J_g u_i)+S_g \quad (2)$$

Where u_i is average flow velocity for porous medium in the i direction, S_g is the additional production rate of gas source term, and J_g is gas diffusion flux.

2.2 Momentum conservation equation

In a given fluid system, the time variation of its momentum is equal to the sum of the external forces acting on it. For porous media, the momentum conservation equation of the i direction in the inertial (non accelerating) coordinate system is:

$$\frac{\partial(\rho_g u_i)}{\partial t}+\frac{\partial}{\partial x_j}(\rho_g u_i u_j)=\frac{\partial \tau_{ij}}{\partial x_j}-\frac{\partial p}{\partial x_i}+\rho_g g_i+F_i \quad (3)$$

Where τ_{ij} is stress tensor, $\tau_{ij}=\mu_{eff}\left[\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-\frac{2}{3}\frac{\partial u_i}{\partial x_i}\delta_{ij}\right]$, δ_{ij} is Kroneker symbol, g_i is the gravity force and the external volume force on the i direction, and F_i is a custom porous media source term.

2.3 Motion equation

Because of the complex gas flow channel in coal and viscous effect, the motion equation of the gas flow in the porous media of coal and rock needs to be described according to different area conditions. According to previous research (Yang et al., 2010), the Navier-Stokes equation is appropriate for describe the fluid flow in the roadway, and the Brinkman equation focuses on the fracture zone while simultaneously considering the characteristics of the fluid pressure and movement, which is appropriate for describing the fluid flow in the caving zone. Using the two equations can build a working face airflow model, as shown in Figure 1. The velocity and pressure on the interface is consistent in the region where the gas flow is in accordance with the Navier-Stokes and Brinkman models. The velocity and pressure distribution of the coal face and goaf can be predicted by solving the model.

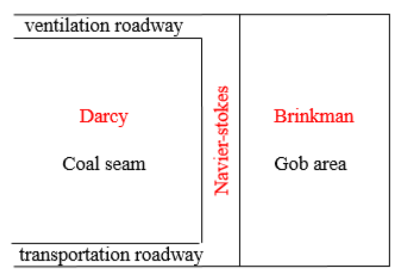


Figure 1: The schematic diagram of description of the fluid motion equation in different areas front and after the working face.

(1) Fluid motion equation in front of working face

To determine the fluid flow with Reynolds number of gas flow in the coal seam, the expression for the Reynolds number, R_e is:

$$R_e=\frac{q \cdot k}{v \cdot d_m} \quad (4)$$

Where q is the gas flow velocity, m/s, k is the permeability, m^2, v is coefficient of kinematic viscosity, m^2/s, d_m is the average particle size, m. When the $R_e \leq 2320$, the fluid flow state is laminar flow, it is transition flow for $2320< R_e<4000$, it is turbulent flow for $R_e \geq 4000$ (Xu xianliang et al., 2011).

When the fluid flow state is laminar flow, the flow in coal bed is in accordance with Darcy's Law:

$$u = -\frac{K}{\mu} \cdot \frac{dp}{dx} \quad (5)$$

Where u is the gas flow velocity in coal bed, m/s, K is the permeability of coal, m^2, μ is dynamic viscosity of the fluid, Pa/s, and d_p/d_x is the fluid pressure gradient.

When the fluid flow state is turbulent flow, the gas flow in the coal bed is Non-Darcy flow, and the fluid pressure gradient can be expressed as follows:

$$-\frac{dp}{dx} = \frac{\mu}{K} u + \beta \rho u^n \quad (6)$$

Where n is related to the characteristics of the porous media of coal, and β is the β-factor of Non-Darcy flow.

The coal permeability in front of the working face is related to its effective stress. Considering the effect of gas pressure, mechanical effect and absorption effect, the expression of the relationship between permeability and effective stress of coal in the condition of mining dynamic loading and unloading is:

$$k = ck_0 \exp\left(d\left\{ \Theta - 3p\left\{ 1 - \frac{3K\left(1-2v_s\right)}{E_s}\left[1 - \frac{\rho RTa \ln\left(1+bp\right)}{p\left(1-\varphi\right)} \right] \right\} \right\} \right)$$

(7)

(2) Fluid motion equation in working face

Navier-Stokes equation can describe the fluid flow in the pipeline. The fluid flow is faster in the working face, and it can be solved by Navier-Stokes equation:

$$-\nabla \cdot \eta \left[\nabla u_{ns} + (\nabla u_{ns})^T \right] - \rho_g \left(u_{ns} \cdot \nabla \right) u_{ns} + \nabla p_{ns} = 0 \quad (8)$$

$$\nabla \cdot u_{ns} = 0$$

Where η is coefficient of viscosity, kg/(m·s), u is velocity vector, m/s, ρ_g is the fluid density, kg/m^3, and p is pressure, MPa. The subscript *ns* means described by the Navier-Stokes equation.

(3) Fluid motion equation in gob area

The Brinkman equation describes a flow between Darcy and Navier-Stokes. The fluid flow in porous media can be described by Darcy's law when the velocity is small, not considering the energy transfer caused by shear stress. When the flow velocity is relatively large, the energy transfer caused by shear stress is considered, and the Brinkman equation is used:

$$-\nabla \cdot \eta \left[\nabla u_{br} + (\nabla u_{br})^T \right] - \left(\frac{\eta}{k} u_{br} + \nabla p_{br} - F \right) = 0 \quad (9)$$

$$\nabla \cdot u_{br} = 0$$

Where the subscript *br* means described by the Brinkman equation.

3. NUMERICAL SIMULATION OF OVERLYING STRATA MOVEMENT LAW IN MINING-INDUCED FRACTURES FIELD

The fracture field is formed within a certain distance in overlying strata above the gob area after coal mining. There are two main types: bed separated fissures and vertical rupture fissures. Overlying strata will have different degree of deformation, resulting in different gas migration and accumulation rules in different positions of the mining-induced fracture field. Therefore, the moving law of overlying strata in mining-induced fractures field simulated by UDEC software is firstly carried out.

3.1 The establishment of numerical model

The 15# coal seam 24080 coal mining working face in No.10 mine of Pingdingshan Tianan Coal Mining Co., Ltd is used as the example case. The calculation model is established according to the integrated histogram and physical and mechanical parameter of coal seam, as shown in Figure 2. The model is 200 m × 100 m, the working face advance distance is 120 m, left and right sides of the recovery boundary reserve 40 m distance from the model boundary to eliminate the boundary effect, and the coal seam is divided into 12 times for excavation, where each time excavates 10 m. The simulated coal seam mining depth is 890 m, the thickness of the coal seam is 2.4 m, the upper boundary is loaded with 20 MPa, and the left or right side and the bottom of the model are normal to the displacement constraint. The bottom boundary limits the vertical displacement. The physical and mechanical parameters of the coal or rock and the mechanical parameters of the joints of model are shown in Tables 1 and 2, respectively.

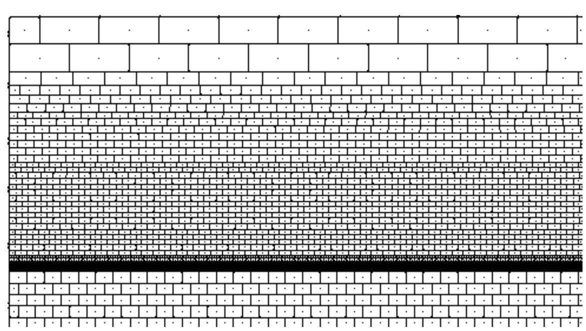


Figure 2: Numerical simulation model.

Table 1: Physical and mechanics parameters of coal or rock.

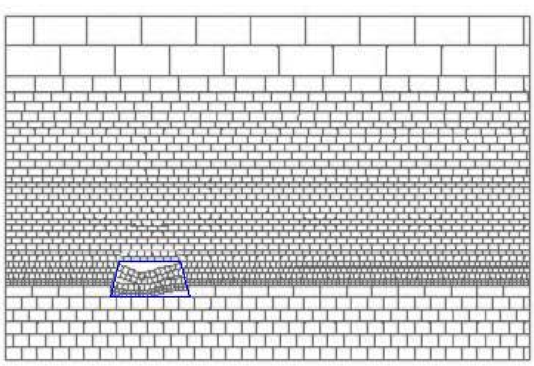
Lithology	Density (kg/cm^3)	Elasticity modulus (GPa)	Compressive strength (MPa)
Mudstone	2.4	17	39
Coal	1.4	13	21
Sandstone	2.8	41	68.5
Sandy mudstone	2.5	20	42.4
Medium-coarse sandstone	3.1	43	70.6
Fine sandstone	2.6	37	58.2

Table 2: Mechanics parameters of joints of the model.

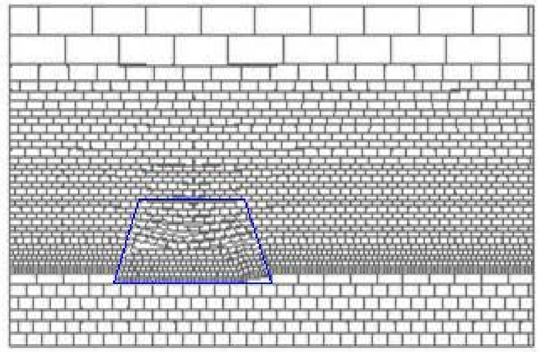
Lithology	Normal stiffness (GPa)	Shear stiffness (GPa)	Frictional angle (°)
Mudstone	7	1	30
Coal	3	0.3	28
Sandstone	21	15	39
Sandy mudstone	14	7	34
Medium-coarse sandstone	25	17	41
Fine sandstone	19	13	37

3.2 The simulated results

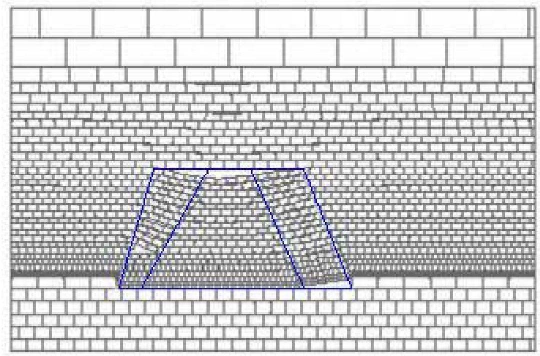
The evolution raw of the fracture field when the excavation distance is 30 m, 60 m, 90 m, and 12 0m is shown in Figure 3. It can be seen from Figure 3 that the overlying strata movement follows a dynamic spatiotemporal evolution process. When the working face is advanced different distances, the overlying strata above the gob area form the mining-induced fracture trapezoidal platform. With increases of the excavation distance, the height of the platform is also increased.



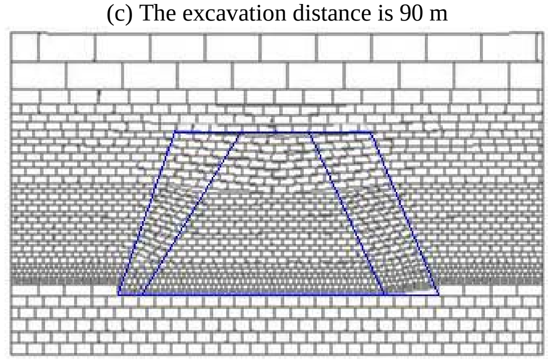
(a) The excavation distance is 30 m



(b) The excavation distance is 60 m



(c) The excavation distance is 90 m



(d) The excavation distance is 120 m

Figure 3: The distribution form of mining fracture field under different excavation distance.

4. NUMERICAL SIMULATION OF GAS MIGRATION IN MINING-INDUCED FRACTURE FIELD

The shape of the mining induced fracture field is obtained using UDEC numerical simulation, and then colour is given to the fracture field, and finally extracted using CORE DRAW software. The fracture distribution of the extracted fracture field is as shown in Figure 4.

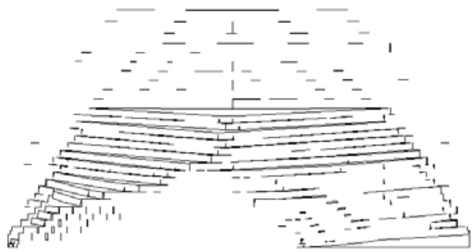
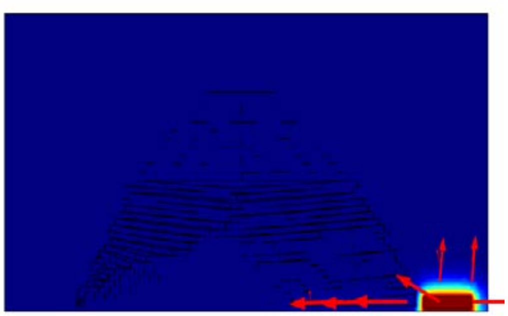
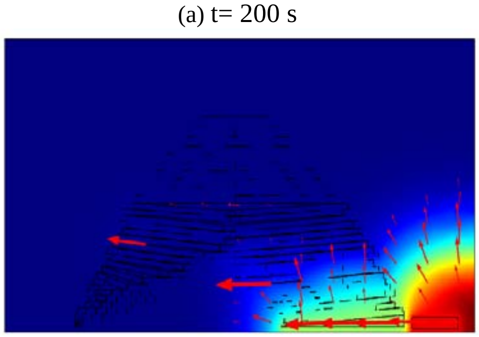


Figure 4: The distribution situation of fracture in the mining fracture field.

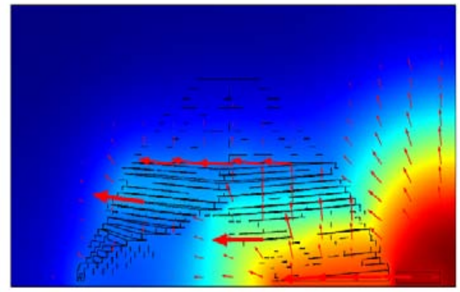
The extracted fracture field is imported into the COMSOL MULTIPHYSICS software for numerical simulation, and the gas migration law at different times in the mining-induced fracture field can be obtained, as shown as Figure 5. The size of the arrow in the figure represents the size of the gas flux. It is clear that the gas flux in mining-induced fracture is far greater than that in the matrix of overlying strata. The bed separated fissures and vertical rupture fissures are the channels of gas flow, compared with the matrix of overlying strata, the gas flow in there has more guiding. With the gas migrate in the mining-induced fracture field, the gas fluxes are larger in the overlying area where the bed separation degree is large. The gas enrichment area is basically located in the largest mining fracture region at the upper end of the trapezoidal table.



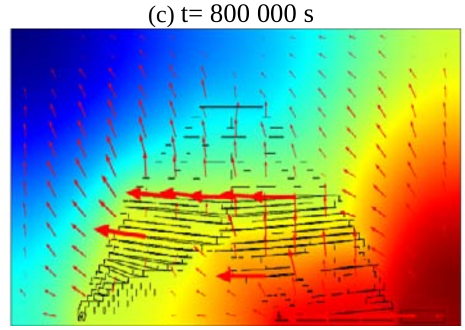
(a) t= 200 s



(b) t= 200 000 s



(c) t= 800 000 s



(d) t= 2 400 000 s

Figure 5: The schematic diagram of gas migration at different time in the mining fracture field.

The schematic diagram of gas concentration nephogram and streamline diagram of gas flux are shown in Figure 6. Assuming that the gas flow to a certain time, the gas concentration in the whole region reaches equilibrium, and the gas drainage is carried out in the fractured zone. From the distribution of gas concentration in Figure 6, it can be seen that the gas concentration in the whole region is falling, and the decreasing rate is relatively large in the fracture development area.

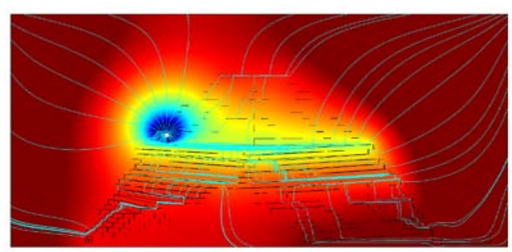


Figure 6: The schematic diagram of gas concentration nephogram and streamline diagram of gas flux.

Figure 7 shows a schematic diagram of gas concentration by height expression. As can be seen from the chart, the height in the surrounding coal matrix descends gently, and it decreases rapidly in the fractured zone of the mining-induced field. Th gas concentration rate decrease in overlying strata matrix is smaller, and in the fractured zone of the mining-induced fracture field the decrease rate is faster, indicating that with the drainage, gas flow orientation in the mining-induced fracture field is stronger.

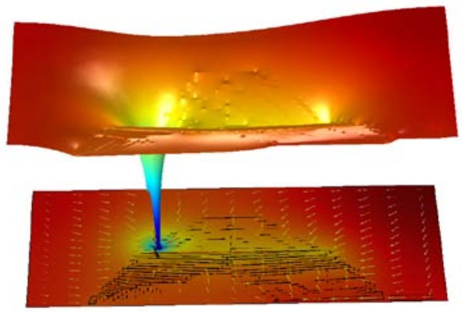


Figure 7: The schematic diagram of gas concentration by height expression.

5. CONCLUSIONS

The mathematical model of gas migration in the coal seam is established according to the flow type in different positions. Using the combination of UDEC software and COMSOL software, the numerical simulation of gas migration in mining-induced fracture above the goaf is carried out. The following conclusions are made:

(1) The movement of overlying strata above goaf is a dynamic spatiotemporal evolution process. With increases of the excavation distance, the areas form the mining-induced fracture trapezoidal platform, and the height of the platform is also gradually increased with excavation.

(2) Compared with the matrix of overlying strata, the gas flows in fractures are more guiding. With the gas migrate in the mining-induced fracture field, the gas enrichment area is located in the largest mining fracture regional at the upper end of the trapezoidal table.

(3) If gas drainage is carried out in the fractured zone, the gas concentration rate decrease in overlying strata matrix is smaller than that in the fractured zone. This means that with the drainage, gas flow orientation in the mining-induced fracture field is stronger.

This paper has carried out a preliminary analysis of gas migration in mining-induced fracture above the goaf using numerical simulation. In the future, the gas content test will be carried out on the scene to validate the simulation results, and to ensure the validity of the model.

6. ACKNOWLEDGEMENT

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