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The Mathematical Model and Numerical Simulation of High Pressure Air Replacement Coal Seam Gas

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Abstract

The high pressure air replaces seam gas is one of effective methods to prevent coal and gas outburst. The paper studied the seam gas flow theory and mathematical model of multi-physics system which coupled the coal deformation, and also worked out the dynamic Mathematical Model both in the pore system and in the fracture system. The coupled models were implemented in the COMSOL Multi-physics, in which the high pressure air injected process was simulated ,and the following conclusions was gained :The injection rate of high pressure air was directly decided by the fracture development, the more a mount of fractures in the coal seams, the higher of the initial coal permeability, and gas transportation in them would be much easier; The gas seepage speed in the fracture system had directionality: The gas seepage speed of fracture system in the horizontal direction is faster than that in the vertical direction; the fracture system plays a more important role in the coal permeability than the role of pore system.

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Keywords: coal matrix; multi-physics coupling; fracture;

1. Introduction

With the increase of the depth of mining coal，both coal seam pressure and the coal seam gas pressure are increasing rapidly. Because of low coal seam permeability and the difficulty of gas extraction, coal and gas outburst is becoming more and more serious [1]. In order to enhance the permeability of coal seam and reduce the mound of work of gas extraction drilling, relevant research institutions have tested a variety of hydraulic techniques and methods, such as coal seam water infusion, coal seam hydraulic

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punching, hydraulic cutting seam, hydraulic fracturing and so on. These measures could reduce the rate of gas desorption by closing gas flow channel ,which was adverse to coal seam gas extraction, although they could increase coal fractures and enhance coal permeability[2-5] .

In order to eliminate coal and gas outburst, intensive drilling have been applied to pump coal seam gas in the especial coal seams which could not have the condition to mine protective layer firstly, but this approach has much adverse effect, such as a large amount of pumping work, a long extraction time and so on[6].

Considering about the actual condition of china mines, the method, high pressure air replaces seam gas, should be applied. It could improve the effect of gas extraction and prevent coal and gas outburst by promoting gas desorption and driving gas to exhausting holes. Not only the inter-space of exhausting holes could be augmented, but the cost and time could be saved.

2. Mechanism analysis

The gas of original coal seam is in a self-balance state, when high pressure air is injected, the air migrates to the coal seam with coal seam fissure system by the impact of its own pressure gradient, after that, the air spreads into coal of matrix. Because of the difference between the air and CH_4, CH_4 will desorbs continuously through the interaction of different gas in coal of matrix, the original absorption locations will be occupy by the injected gas. The absorbed methane is gradually decreasing, and the detached methane is increasing by degrees. As the mode of occurrence is extremely complicated, the methane cannot be totally but mostly desorbed.

The mechanism of injecting high pressure air to displace the coal bed methane can be concluded as fallow:

- Injected air maintains high pressure gradient of coal seam fluid, and supplies the fluid flow with continuously power which drives not only injected fluid, but also desorbed fluid.
- Play the role of anatonosis from N_2. N_2 is about 78 percent of air volume, its absorbability is weaker than CH_4, so the coal seam will shrink when N_2 displaces CH_4, and the coal seam permeability will be remarkable increased [7].
- Play the role of competitive absorption from CO_2. There is a small quantity of CO_2 in the air, its absorbability is stronger than CH_4 which will replace the original absorption potential of methane by some kind of competitive absorption mechanism, and facilitate methane’s desorption.

3. Mathematical models

When the high pressure air is injected into coal seam, not only the mechanical properties of coal matrix will be changed, but the seam deformation also occurred. The gas absorped on the surface of coal matrix could make coal seam bulge, which would decrease both the permeability of coal and the space to store gas. Hence the process is complex. The establishment and derivation of the mathematical models should be based on the following assumption conditions:

- Coal is an elastics double porous medium filled with holes and fractures;
- Little deformation of coal matrix is presumed;
- The gas in the coal seam is ideal;
- The migration of gas flow includes three kinds of stages, which are desorption, diffusion, and seepage flow. The flow inside the factures is the kind of isothermal flow and suit to Darcy law. And the material exchange of gas between the micro-holes and fractures obeys the Fick low.

3.1. Coal matrix deformation control equation

Geometric equations:

$$\varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}) \quad i=1，2，3 \ j=1，2，3 \tag{1}$$

Balance stress equation:

$$\sigma_{ij,j} + f_i = 0 \tag{2}$$

Constitutive equation which is based on Porous media elasticity theory [8]:

$$\varepsilon_{ij} = \frac{1}{2G}\sigma_{ij} - (\frac{1}{6G} - \frac{1}{9K})\sigma_{kk}\delta_{ij} + \frac{\alpha}{3K}p_m\delta_{ij} + \frac{\beta}{3K}p_f\delta_{ij} + \frac{\varepsilon_s}{3}\delta_{ij}\sqrt{2} \tag{3}$$

$$C_1 = \frac{1}{E}，\ C_2 = \frac{1}{K_n a}，\ D = \frac{1}{C_1 + C_2}，\ G = \frac{D}{2(1+\nu)}，\ K = \frac{D}{3(1-2\nu)}$$

$$\alpha = 1 - \frac{K}{K_s}，\ \beta = 1 - \frac{K}{K_n a}$$

Where E is elastic modulus, G is shear modulus, σ_{kk} is the component of normal stress，p is Pore pressure,ε_s is adsorption strain，α is the Biot coefficient of coal matrix, β is the Biot coefficient of fracture. K is coal bulk modulus， K_s is coal matrix bulk modulus, K_n is the normal stiffness of single fracture.δ_{ij} is Kronecker mark. The subscript m denotes coal matrix parameter, the subscript f denotes coal fracture parameter.

Combine equations (1) (2) and equation (3), we can get coal matrix deformation control equation:

$$Gu_{i,kk} + \frac{G}{1-2\nu}u_{k,ki} - \alpha p_{m,i} - \beta p_{f,i} - K\varepsilon_{s,i} + f_i = 0 \tag{4}$$

3.2. Gas motion control equation

Coal seam gas quality balance equation:

$$\frac{\partial m}{\partial t} + \nabla \cdot (\rho_g \overrightarrow{q_g}) = Q_s \tag{5}$$

Where m is the gas quality of unit volume coal, ρ_g is coal seam gas density, $\overrightarrow{q_g}$ is Darcy law velocity vector， Q_s is gas supply source, t is time.

The gas quality of coal seam includes two states: free and absorbed, and the gas in the coal fracture is free. The gas quality in the coal matrix of unit volume coal can be defined with equation (5), and the gas quality in the coal fracture of unit volume can be defined with equation (6).

$$m_m = \rho_g \phi_m + (1-\phi_m)\rho_{ga}\rho_c \frac{V_L p_m}{p_m + p_L} \tag{6}$$

$$m_f = \rho_g \varphi_f \tag{7}$$

Where φ is coal porosity, V_L is Langmuir bulk constant, p_L is Langmuir pressure constant. The subscript *m* denotes coal matrix parameter, the subscript *f* denotes coal fracture parameter, the subscript *g* denotes gas.

According to Darcy's law, we can get gas velocity vector:

$$\overrightarrow{q_g} = -\frac{k}{\mu}\nabla p \tag{8}$$

Where *k* is coal permeability, μ is gas dynamic viscosity coefficient.

Substitute equations (6) (7) (8) into equation (5), and get the gas motion equations in the coal matrix and coal fraction.

$$\left[\phi_m + (1-\phi_m) p_{ga}\rho_c \frac{V_L P_m}{p_m + p_L}\right]\frac{\partial p_m}{\partial t} + P_m \frac{\partial \phi_m}{\partial t} + \nabla\cdot\left(-\frac{k_m}{\mu} p_m \nabla p_m\right) = \omega\left(p_f - p_m\right) \tag{9}$$

$$\phi_f \frac{\partial \phi_f}{\partial t} + p_f \frac{\partial \phi_f}{\partial t} + \nabla\cdot\left(-\frac{k_f}{\mu} p_f \nabla p_f\right) = -\omega\left(p_f - p_m\right) \tag{10}$$

$$\omega = 8\left(1+\frac{2}{a^2}\right)\frac{k_m}{\mu} \tag{11}$$

Where p_a is standard atmospheric pressure, ω is gas quality exchange coefficient between coal matrix system and coal fraction system.

3.3. Permeability model

After the injection of high pressure air, the pressure between fractures in the coal layer would increase. After that, the air was absorbed on the surface of coal particles when it diffused into the coal matrix. The absorbed gas could lead seam expansion, in the other hand, desorbed would make contraction transformation of coal matrix .This kind of transformation has a great impact not only on the porosity but also on the seepage flow rate in coal layer. Therefore, the dynamic change processes of coal seam porosity and coal seam permeability have great importance to eliminate coal and gas burst.

During the injection of high pressure gas, the changing model of permeability in coal matrix is as follows[8]:

$$\frac{k_m}{k_{m0}} = \left(1 - \frac{\alpha}{\phi_{m0} K} \cdot \frac{1}{\frac{b_0}{aK_f} + \frac{1}{K}} \left(\frac{\varepsilon_L p_L \left(p_m - p_{m0} \right)}{\left(p_L + p_m \right)\left(p_m + p_{m0} \right)} - \varepsilon_v \right) \right) \tag{12}$$

Where k_m is permeability of coal matrix, k_{m0} is original permeability of coal matrix, K is bulk modulus of coal matrix, $K = E/3(1-2\nu)$, φ_{m0} is original porosity of coal matrix, α is Biot coefficient of coal matrix, $\alpha = 1-K/K_s$, K_s is bulk modulus of coal matrix, a is the breadth of coal matrix, b_0 is the original breadth of coal fracture, K_f is the equal bulk modulus of coal fracture, $K_f = a\ K_n$, K_n is coal fracture rigidity, ε_L is Langmuir bulk strain constant. The subscript *0* denotes original coal value, the subscript *m* denotes coal matrix.

The change model of permeability in coal fracture is as follows [9]:

$$\frac{\phi_f}{\phi_{f0}} = 1 - \frac{3}{\phi_{f0} + \frac{3K_f}{K}} \left(\frac{\varepsilon_L p_L \left(p_m - p_{m0} \right)}{\left(p_L + p_m \right)\left(p_m + p_{m0} \right)} \right) \tag{13}$$

$$\frac{K_f}{K_{f0}} = \left(1 - \frac{3}{\phi_{f0} + \frac{3K_f}{K}} \left(\frac{\varepsilon_L p_L \left(p_m - p_{m0} \right)}{\left(p_L + p_m \right)\left(p_m + p_{m0} \right)} \right) \right)^3 \tag{14}$$

The subscript 0 denotes original coal value, the subscript *f* denotes coal matrix.

3.4 Gas flow mathematical model

Substitute equations (12) (14) into equation (9) (10), and we can get the ultimate gas motion control equations in the coal matrix and coal fraction.

$$S_m \frac{\partial p_m}{\partial t} + \nabla \cdot \left(-\frac{k_m}{\mu} p_m \nabla p_m \right) = \omega \left(p_f - p_m \right) \tag{15}$$

$$S_f \frac{\partial p_f}{\partial t} + \nabla \cdot \left(-\frac{k_f}{\mu} p_f \nabla p_f \right) = \omega \left(p_f - p_m \right) \quad (16)$$

$$S_m = S_{m1} + S_{m2} + S_{m3} + S_{m4},\ S_{m1} = \phi_m,\ S_{m2} = \left(1-\phi_{m0}\right) p_{ga} \frac{V_L p_L}{\left(p_L + p_m\right)^2},$$

$$S_{m3} = -\frac{\alpha K_f}{\frac{b_0}{a} K + K_f} \cdot \frac{\varepsilon_L p_L p_m}{\left(p_L + p_m\right)^2},\ S_{m4} = \frac{\alpha K_f}{\frac{b_0}{a} K + K_f} \cdot p_m \frac{\partial \varepsilon_v}{\partial p_m}$$

$$S_f = S_{f1} + S_{f2} + S_{f3},\ S_{f1} = \phi_f,$$

$$S_{f2} = -\frac{3\phi_{f0} p_f}{\phi_{f0} + \frac{3K_f}{K}} \cdot \frac{\varepsilon_L p_L}{\left(p_L + p_m\right)^2} \frac{\partial p_m}{\partial p_f},\ S_{f3} = -\frac{3\phi_{f0} p_f}{\phi_{f0} + \frac{3K_f}{K}} \frac{\partial \varepsilon_v}{\partial p_f}$$

4. Numerical simulation

COMSOL Multi-physics was used in this paper to make numerical research on the replacement of high pressure air with coal seam gas. The size of established model is 200×200m, and the thickness of coal seam is 2.0m. The injection hole is in the middle of the model, of which one-fourth is studied for its symmetry. The pressure of the injected air is 8.5MPa. The boundary of model is no outflow boundary for the gas flow equation.

4.1. Related parameter

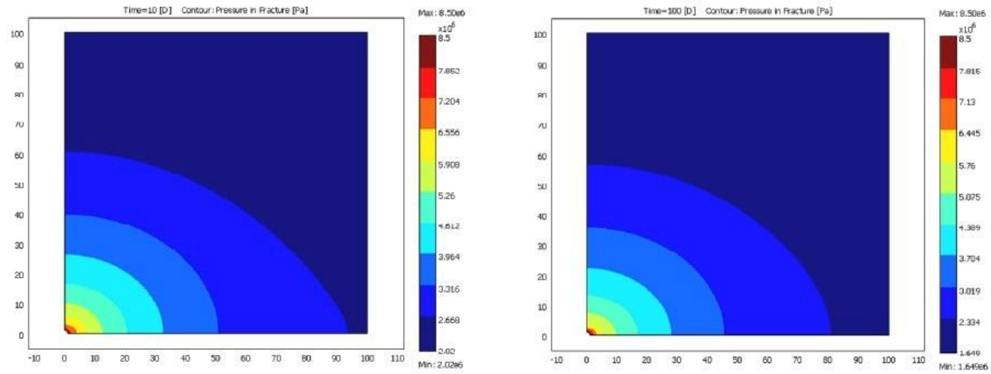
Table1. Property parameters of simulation model

Attribute	Value
Elastic modulus of coal, *E (M Pa)*	2710
Elastic modulus of coal matrix, *E (M Pa)*	8240
Poisson ratio, v	0.335
Coal density, ρ_c(kg/m^3)	1385
Air density(standard state), ρ_c(kg/m^3)	1.293
Air Langmuir pressure constant, P_L *(M Pa)*	3.876
Air Langmuir bulk constant, V_L *(M Pa)*	0.0357
Air Langmuir bulk strain constant, ε_L *(M Pa)*	0.01683
Original porosity of coal matrix, φ_{m0}	0.03
Original permeability of coal matrix, $k_{m0}(m^2)$	10-17
The breadth of coal matrix, (m)	0.005

Table2. Air injection quantity

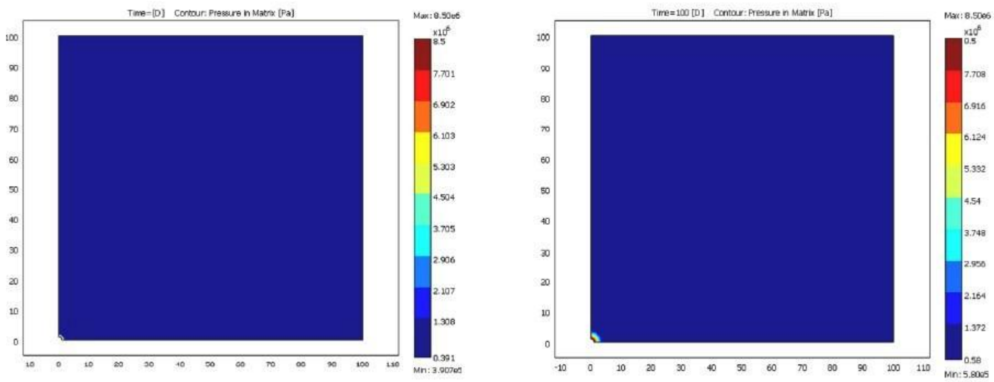
time	The 10th day	The 100th day
Daily injected gas quantity / m^3	3535	2711
Accumulated injected gas quantity / m^3	34661	291278

4.2. The distribution of gas pressure



(a) 10D (b) 100D

Figure.1.The pressure distribution in fracture



(a) 10D (b) 100D

Figure.2.The pressure distribution in matrix

4.3. Results

From the above figures, the gas seepage speed in the fracture system was fast and had directionality. The gas seepage speed of fracture system in the horizontal direction is faster than that in the vertical direction. As the vertical stress acting on the model is heavier than the horizontal stress, the gas could flow easily in the horizontal direction. This is consistent with the actual situation.

More a mount of fractures in coal seam, the greater initial permeability of the seam, and the gas could have a fast seepage speed. Moreover, the mass fractures could also make more contact spaces for gas and matrix, which was beneficial to gas absorption. The air could replace more a mount of coal seam gas at the same time. Comparing figure.1 to figure.2, we could get that matrix porosity had a little effect on coal permeability.

5. Conclusions

Based on the mechanism and mathematical model of high-pressure air replaces coal seam gas, we can get the following conclusions:

- That high-pressure air injured into the coal seam will have a significant impact on gas pressure gradient, which is beneficial to gas desorption and gas flow. With the impact of the pumping pressure, this kind of flow will be much faster, to achieve the purpose of gas drainage.
- Coal seam permeability is determined by coal fracture system. In engineering practice, we must fully consider the circumstances of coal seam fractures to design the distance between the injection holes and the drainage hole, to get a good extraction result.
- The process of high-pressure air replace coal seam gas is quite complex, the roles of each component of mixed-gas playing are unclear, therefore, further study should be taken.

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