Numerical analysis of coal seam heat injection

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Abstract. Coal seam heat injection is a new type of enhanced gas drainage method. In order to obtain the influence law of coal seam heat injection on the gas content in coal, the coupled equation of heat, fluid and solid multiphysics under coal seam heat injection is used to solve it with the help of numerical analysis software. The law of coal gas content change under the condition of coal seam heat injection is obtained: During the process of coal seam heat injection, the temperature of the coal near the heat injection borehole is relatively high. With the increase of the heat injection temperature, the adsorbed gas content in the coal gradually decreases, the free gas increases, and the residual gas content of the coal decreases more significantly. The extraction time was effectively shortened, and the expected goal of heat injection enhanced extraction was achieved.

1. Project overview
Drawing lessons from thermal flooding technology in the petroleum industry, scholars at home and abroad have proposed the idea of coal seam heat injection and drainage [1-2]. After the coal seam is injected with heat, it not only affects the structural deformation characteristics of the internal pores and cracks of the coal, but also has a great impact on the law of gas adsorption and desorption and seepage in the coal, the change of coal permeability and the effect of gas drainage. Theoretically, the coupled equations of thermal fluid-solid multiphysics under coal seam heat injection are complex partial differential equations, which can only be solved by numerical analysis methods. In addition, the use of numerical analysis can make up for the deficiencies in laboratory experiments and help to better study the law of coal seam heat injection on the change of gas content in coal.

2. Coal seam heat injection theory model
The process of coal seam heat injection is an extremely complex multi-physical field coupling problem. The change of coal permeability during the heat injection process is also the result of a combination of many factors. In order to facilitate the numerical analysis and research, certain assumptions must be made for the coal seam heat injection process: (1) The coal body is an elastic porous uniform medium; (2) The deformation of the coal body conforms to the law of solid mechanics; (3) The dynamic viscosity of coalbed methane is considered constant; (4) The seepage flow of coalbed methane conforms to Darcy's law; (5) The heat transfer of coal body conforms to the heat transfer model of porous media.
On the basis of the basic assumptions of the numerical simulation, through the establishment of the mathematical equations of the heat-fluid-solid three-fields of the coal seam heat injection process and the analysis of the coupling factors, and the influencing effects of various physical fields and related factors, the coal seam heat injection process can be obtained. Heat-fluid-solid three-field coupling equation. [3-8]

1) Seepage field equation

\[ C = C_0 + C_s = \frac{\rho_n (\phi + \varphi) \rho_0}{P_a} + \frac{abcP_0}{1 + bP} \times \exp \left[ -\frac{0.02}{1 + 0.07P} \right] \]  
Gas content equation (a)

\[ \text{div}(\rho \mathbf{q}) = \frac{\partial C}{\partial t} \]  
Continuity equation (b)

\[ \frac{\rho_0 P}{Z_0} \]  
Equation of state (c)

\[ J_{\varepsilon} = -D \frac{\partial C}{\partial t} \]  
Diffusion equation (d)

\[ V = \frac{k}{\rho} \]  
Percolation equation (e)

\[ k = k_{so} = \left[ 1 + \frac{1}{\phi_i} \left( \frac{\varepsilon_i P_0 (p_{so} - p_{mo})}{(p_i + p_{so})(p_i + p_{mo})(1 + \chi \cdot W)} + \frac{\alpha \Delta T}{K} \right) \right]^3 \]

\[ k = k_{so} = \left[ 1 - \frac{\Delta T}{K} - \frac{\alpha \Delta T}{3} \right] \]

(1)

2) Stress field equation

\[ Gu_{i,\varepsilon_{i,j}} + \frac{G}{1 - 2\nu}u_{i,\varepsilon_{i,j}} - \alpha_s K T_{i,j} - \alpha P_{i,j} - K \left( \frac{\varepsilon_i P_2}{(p + P_2)} \right)^{(1 + \chi W)} f_{i,j} = 0 \]  

\[ (2) \]

3) Temperature field equation

\[ \rho C T + \frac{\partial}{\partial t} + \frac{\partial}{\partial \varepsilon_i} \left( \rho C_i \right) \]  

\[ \frac{\partial}{\partial t} + \Delta T \rho C_i \frac{\partial}{\partial \varepsilon_i} \left[ \frac{\phi_i}{1 + (\varepsilon_i - \varepsilon_0)} + \gamma \Delta T + \frac{\Delta \sigma}{K} + \frac{\Delta \sigma}{K} \right] + T \sigma, \kappa \frac{\partial}{\partial \varepsilon_i} \]

\[ + \phi_i \left[ 1 - \frac{\Delta \sigma}{K} \right] + \rho C_i \Delta TV \frac{\partial}{\partial \varepsilon_i} + \nabla (\kappa \nabla T) = Q_T \]  

Through formulas (1) ~ (3), the boundary conditions and initial conditions of the multi-physics field suitable for coal seam heat injection are determined, and the law of coal seam heat injection on gas content changes in the coal body can be finally obtained.

3. Numerical analysis of coal seam heat injection

3.1. Geometric model and solution parameters
The vertical shaft of a mine in Shanxi is selected as the geometric model. The net diameter of the shaft is 7.0m, which is mainly responsible for the air return task of the mine. The coal seam is stable and simple in structure. It is a near-level coal seam. The hydrogeological conditions in the minefield are simple. The coal seam has the risk of coal and gas outburst.
Fig. 1 Schematic diagram of the wellbore geometry model

In order to facilitate the selection of the two-dimensional geometric model as the research object, the meshing of the geometric model is shown in Figure 1. In Figure 1, there are 9 holes distributed with a diameter of 75mm. The simulation scheme is divided into two types: extraction only and heat injection extraction. The layout of the boreholes is shown in Figure 2. The hollow circles indicate the extraction holes and the solid circles indicate the injection hot spots. In order to simplify the calculation, the gas drainage borehole control area only includes the vertical area of the wellbore, excluding the area outside the wellbore contour. According to the symmetry of the model, a 1/4 model is selected for calculation, as shown in Figure 3.

Drilling only

Heat injection and extraction

○—Drainage hole; ●—heat injection drilling

Fig. 2 The numerical simulation program

Fig. 3 Schematic diagram of numerical model

The original gas content is about 14m³/t, the initial gas pressure of the coal seam is 1.5MPa, and the initial temperature is 293K. The specific parameters of the model solution are shown in Table 1.
Table 1. The parameter of model

| Model parameters | Physical description | Value | Model parameters | Physical description | Value |
|------------------|----------------------|-------|------------------|----------------------|-------|
| \(a\)            | Gas adsorption      | 24.63 | \(k_{f_0}\)      | Initial permeability of fracture | \(1 \times 10^{-18} \text{m}^2\) |
| \(b\)            | Gas adsorption      | 0.9556| \(\rho_g\)       | Initial gas density   | 0.717 \text{kg/m}^3 |
| \(\rho_s\)       | Coal density        | 1330kg/m\(^3\) | \(\mu\)          | Gas dynamic viscosity | \(1.08 \times 10^{-5} \text{Pa} \cdot \text{s}\) |
| \(\rho_c\)       | Coal skeleton       | 1270kg/m\(^3\) | \(C_g\)          | Gas specific heat capacity | 2270J/(kg·K) |
| \(E\)            | Young's modulus of  | 2.713×10\(^9\)Pa | \(C_s\)          | Specific heat of coal  | 1260 J/(kg·K) |
| \(E_s\)          | Young's modulus of  | 8.139×10\(^9\)Pa | \(\alpha_s\)     | Thermal expansion coefficient of coal | \(0.1 \times 10^{-6} \text{J/(m} \cdot \text{s} \cdot \text{K})\) |
| \(\phi\)         | Initial porosity    | 0.0423| \(\lambda_s\)    | Thermal conductivity of coal | 4.35W/(m·K) |
| \(\varphi\)      | Initial crack rate  | 0.001 | \(\lambda_g\)    | Gas thermal conductivity | 0.03 W/(m·K) |
| \(k_{m_0}\)      | Initial pore        | \(3 \times 10^{-19} \text{m}^2\) | \(W\)            | Coal seam original moisture | 0.0043 |
| \(P_n\)          | Standard atmosphere | 0.101325MPa | \(A\)            | Coal seam ash         | 0.0979 |
| \(M_g\)          | Molar mass          | 16g/mol| \(T_1\)          | Injection temperature | 453K |
| \(T_0\)          | The initial         | 293K  | \(P_0\)          | Initial gas pressure  | 1.5MPa |
| \(D_s\)          | Diffusion coefficient | 2.16×10\(^{-3}\) |                  |                     |       |

3.2. Theoretical modules and numerical analysis

Based on the multi-physics theoretical model, Darcy’s law module, solid mechanics module and porous media heat transfer module are selected in the multi-physics coupling numerical analysis software to form the coal seam heat injection multi-field coupling module, and coal permeability is added to the coupling module Rate evolution model and definite solution conditions, and perform corresponding numerical solutions. The conditions for the solution are as follows:

(1) Conditions for definite solution of seepage field
Gas pressure: \( p = p_0 \big|_{t=0} \); Coal seam boundary gas flow: \( q_s = 0 \); Boundary pressure of drainage borehole: \( p = p_2 \).

(2) Conditions for definite solution of temperature field
Internal temperature of coal seam: \( T_0 = 298K \); Temperature field boundary conditions: \( T = T_i \).

(3) Conditions for definite solution of stress field
At \( t=0 \), the coal seam displacement field and velocity field are zero, \( u \big|_{t=0} = 0; \ \frac{\partial u}{\partial t} \big|_{t=0} = 0 \); The upper boundary is subject to boundary load \( F = F_\alpha \); the two sides of the boundary are supported by rollers; the lower boundary is subject to fixed constraints.

In the theoretical model, the three modules are interconnected and coupled with each other. The model heat injection temperature \( T_1 \) is set to 298K, 423K, 453K, and the transient solver is used to solve the model. In order to facilitate the analysis, take the two-dimensional intercept point on the geometric plane for research, and the specific position of the intercept point is shown in Figure 4.
3.3. Solution results and analysis

Take the residual gas content at the two-dimensional intercept point in Figure 4 as the assessment index. Through the transient solution of the model, the change law of the residual gas content in the coal body within the range of the wellbore contour line under the conditions of heat injection and extraction alone can be calculated, and the residual gas content at the two-dimensional intercept point in the model can be solved. The change rule of the extraction time is the research object, and the solution result is shown in Figure 5.

![Fig. 4 The cut-off point location map](image)

![Fig. 5 The residual gas content of cut point changes with time curve](image)

It can be seen from Fig. 5 that the residual gas content of the coal seam at the two-dimensional intercept point of the solution model is significantly reduced under the heat injection enhanced drainage condition, which effectively shortens the drainage time and achieves the heat injection. The expected goal of strengthening drainage. This is because the increase in temperature promotes the desorption of coal body gas around the injection hot spot, which reduces the adsorbed gas content, increases the free gas content, and gradually increases the gas pressure. As the heat injection progresses, this trend gradually extends to the entire model. Although the local permeability of the coal seam has decreased, the increase in gas pressure increases the pressure gradient of the coal seam. Under the action of the drainage boreholes, the flow of gas drainage boreholes gradually increases, resulting in a certain degree of gas drainage rate, improve.

4. Conclusion

Based on the thermal fluid-solid multi-physical field coupling model under the coal seam heat injection condition, numerical analysis software is used to numerically analyze the coal seam gas content change rule under the heat injection condition. Numerical analysis results show that after the coal temperature rises, the desorption of coal gas around the injection hot spot is promoted, so that the adsorbed gas content gradually decreases, and the free gas content gradually increases. Under the action of drainage
boreholes, the coalbed gas content decreases. The range has been significantly increased, and the effect of coal seam gas drainage has been strengthened.

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