EFFECT OF TEMPERATURE ON GAS SEEPAGE CHARACTERISTIC BASED ON COAL–GAS INTERACTION MODEL

by

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The temperature has a significant impact on the coal seam gas (CSG) extraction. A fully coupled model is established in this study, which takes into account the coal–gas interaction characteristic. The numerical result shows that the coalbed methane migration and transport evolution coal bed methane reservoir is not only dependent on the coal matrix deformation, gas pressure and gas adsorption, but also closely related to temperature.

Key words: Gas extraction, thermo-hydro-mechanical model, temperature, Partial differential equations (PDEs)

Introduction

The main component of coal seam gas is methane, which is a potentially valuable energy resource, but also a potential coal mine disaster. Coal bed methane extraction is an effective method to reduce the gas disaster. Besides, gas drainage can take advantage of this clean energy source [1-3]. The extraction process of coal bed methane depends on our understanding of the methane migration and gas-coal interaction. Coal seam is the dual porous media reservoir, containing matrix and fracture network. Coal matrix is the main gas reservoir space, and the fracture network system can provide an effective gas flow path [4-6].

This fluid flow and solid deformation problem gets a lot of attention. Scholars have proposed many models to analyze the coal and methane interaction [7-9]. In deep strata, temperature has a significant effect on coal seams. Temperature will affect the adsorption of coal seam and change the effective influence of coal, and then change the permeability of coal seam, affecting the flow of gas. On the whole, it is a complex coal-gas interaction process [10-12].

In this paper, a coupled model (gas flow, solid deformation and temperature change) is established. Through this finite element model, the effect of temperature on coal

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seams was quantitatively analyzed. The model and the simulation results can provide the scientific basic for the analysis of the gas flow characteristic in extraction process.

Equations of coupled model

Gas Flow in Fractures

The non-Darcy is usually adopted in coal seam gas extraction and it can be expressed as [13,14]:

$$-\nabla p_f = \frac{\upsilon}{k_g}\vec{\mu}\,, \tag{1}$$

where $\vec{\mu}$ is the velocity, ρ_g is the density, and k_g is the permeability.

For the porous media, the flow equilibrium equation can be expressed as:

$$\frac{\partial}{\partial t}(\phi_f \rho_g) + \nabla(\rho_g \cdot \vec{\mu}) = Q_s(1-\phi_f)\,, \tag{2}$$

where Q_s is the gas source. The mass content m is calculated as:

$$m = \rho_g \phi_f + \rho_{ga}\rho_c V_{sg}\,, \tag{3}$$

where ρ_{ga} is the gas density at standard condition, ρ_c is the coal density, and V_{sg} is the content of absorbed gas.

The gas absorption volume can be expressed as:

$$V_{sg} = \frac{V_L p_f}{p_f + P_L}\exp[-\frac{c_2}{1+c_1 p_f}(T_{ar} + T - T_t)]\,, \tag{4}$$

where V_L and P_L are the Langmuir volume constant and Langmuir pressure constant, respectively, c_1 the pressure coefficient, and c_2 the temperature coefficient.

The sorption induced volumetric shrinkage strain ε_s is assumed as:

$$\varepsilon_s = \alpha_{sg} V_{sg}\,, \tag{5}$$

where V_{sg} is the content of absorbed gas, and α_{sg} is the sorption-induced strain coefficient.

The ideal gas law is described as:

$$\rho_g = \frac{M_g}{R(T_{ar} + T)}p\,, \tag{6}$$

where ρ_g is the gas density, M_g is the molecular weight of the gas, T is the gas temperature, R is the universal gas constant, and p_a is the standard atmospheric pressure.

Then the gas flow equation can be rewritten as [15]:

$$\frac{\rho_{ga}}{p_a}\frac{\partial(\phi_f p_f)}{\partial t} + \nabla(-\frac{k_g}{\mu}\rho_g \nabla p_f) = Q_s(1-\phi_f)\,, \tag{7}$$

Mechanical equilibrium equation

For the dual porosity media, the effective stress can be expressed as:

$$\sigma_{eij} = \sigma_{ij} - \alpha p_f \delta_{ij}, \tag{8}$$

where σ_{eij} is the effective stress, δ_{ij} is the Kronecker delta tensor, and α is effective stress coefficients for coal fractures.

The strain-displacement relation of coal is expressed as:

$$\varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}), \tag{9}$$

The Navier-type equation is yielded as:

$$Gu_{i,jj} + \frac{G}{1-2\mu}u_{j,ji} - \alpha p_{f,i} - K\alpha_T T_{,i} - K\varepsilon_{s,i} + f_i = 0, \tag{10}$$

Coal permeability

The general porosity model is defined as [16]:

$$\Delta\phi_f = \frac{1}{K}(\beta_f - \phi_f)(\bar{\sigma} + p_f), \tag{11}$$

Then the porosity is expressed as:

$$\phi_f = \alpha - (\alpha - \phi_0)\exp\{-\frac{1}{K}[(\bar{\sigma} - \bar{\sigma}_0) + (p_f - p_{f0})]\}, \tag{12}$$

where subscript 0 denotes the initial state of variables.

Substituting the porosity can be rewritten as:

$$\phi_f = \alpha - (\alpha - \phi_{f0})\exp\{-[(\varepsilon_V + \frac{p_f}{K_s} - \varepsilon_s - \alpha_T T) - (\varepsilon_{V0} + \frac{p_{f0}}{K_s} - \varepsilon_{s0} - \alpha_T T_0)]\}, \tag{13}$$

where p_0 is the initial pressure, and ϕ_0 is the initial porosity.

The permeability is correlated to the porosity according to the following exponential function:

$$\frac{k_g}{k_{\infty 0}} = \frac{k_\infty}{k_{\infty 0}}(1 + \frac{b}{p_f}) = (\frac{\phi}{\phi_0})^3(1 + \frac{b}{p_f}), \tag{14}$$

Energy evolution

Neglecting the interconvertibility of thermal energy, the thermal balance is obtained as:

$$\frac{\partial[(\rho C)_M (T_{ar} + T)]}{\partial t} + (T_{ar} + T)K_g\alpha_g\nabla\cdot(\frac{k_g}{\mu}\nabla p) + (T_{ar} + T)K\alpha_T\frac{\partial\varepsilon_V}{\partial t} = -\nabla\cdot q_T, \tag{15}$$

where $(\rho C)_M$ is the specific heat capacity of solid medium, $(\rho C)_M = \phi_f(\rho_g C_g) + (1-\phi_f)(\rho_s C_s)$, and ρ_s the mass density of coal matrix.

The conservation of mass of the two phases can be written as:

$$\frac{\partial[(1-\phi_f)\rho_s]}{\partial t} = 0, \tag{16}$$

$$\frac{\partial(\phi_f \rho_g)}{\partial t} = -\nabla\cdot(\rho_g q_g), \tag{17}$$

Considering $(1-\phi)\lambda_s \gg \phi\lambda_s$ and $\lambda_M \approx (1-\phi_f)\lambda_s \approx \lambda_s$, then yields

$$\begin{aligned}(\rho C)_M \frac{\partial T}{\partial t} - (T_{ar}+T)K_g\alpha_g\nabla\cdot\left(\frac{k_g}{\upsilon}\nabla p_f\right) + (T_{ar}+T)K\alpha_T\frac{\partial\varepsilon_V}{\partial t} = \lambda_M\nabla^2 T \\ + \frac{\rho_{ga} p_f T_a C_g}{p_a(T_{ar}+T)}\frac{k_g}{\upsilon}\nabla p_f \nabla T\end{aligned}, \tag{18}$$

The full coupled model can be used to analyze the temperature process. The cross coupling variable (porosity and permeability) connects different physical fields.

Model establishment and numerical simulation

Model establishment

In order to analyze the effect of temperature on the gas extraction, a calculation model is established as shown in Fig. 1. The length is 100m and width is 100m. The four boundaries are restrained by normal displacement. The zero fluxes are applied to these boundaries. The initial pressure is 3MPa, the initial temperature of the coal seam is 363K. The drainage pressure is 0.1 MPa and the temperature is 303 K. A monitoring line is selected in diagonal line of coal mass to study the change law of coal permeability and gas pressure.

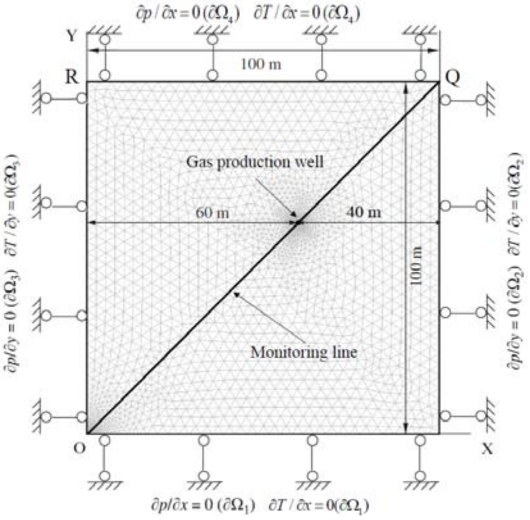
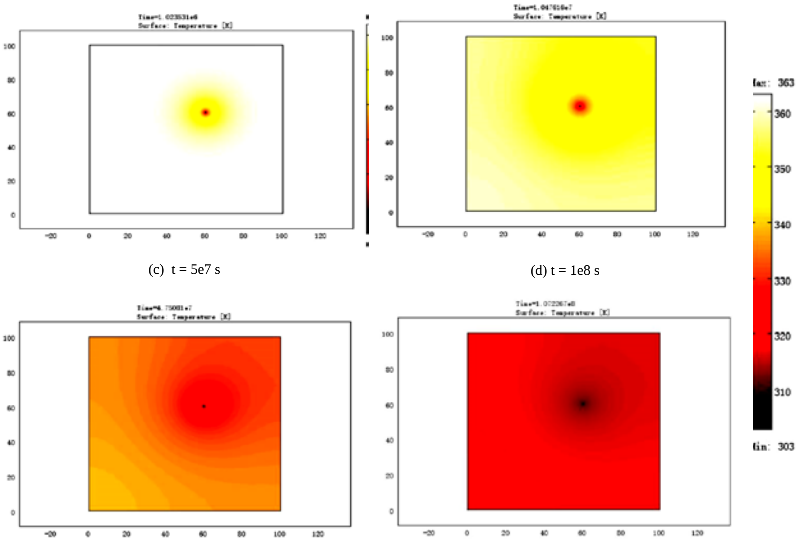


Fig. 1. Computational model and schematic diagram.

Temperature evolution law and gas pressure evolution law


(a) t = 1e6 s

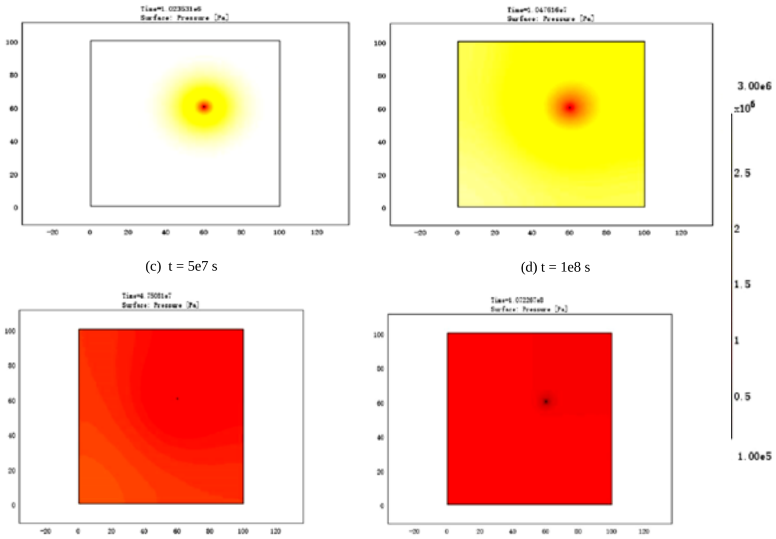
(b) t = 1e7 s

(c) t = 5e7 s

(d) t = 1e8 s

Fig. 2. Distribution of temperature at different times.

Fig. 2 shows the temperature distribution at different production times. The temperature gradually reduces gradually during the extraction process. The temperature maximum gradually decreases from 363K to 319 K at production time from 1×10^6 s to 1×10^8 s. High temperature accelerate the gas flow, which is beneficial to the extraction of coal seam. Fig. 3 shows the evolution of gas pressure with the extraction time. With the increase of time, the gas pressure reduces. The gas pressure is affected by the gas content, temperature and the permeability of the coal seam. The pressure drop near the borehole is larger, and the gas pressure decreases slowly away from the well.


(a) t = 1e6 s

(b) t = 1e7 s

(c) t = 5e7 s

(d) t = 1e8 s

Fig. 3. Distribution of gas pressure at different times.

Permeability evolution and gas pressure distribution

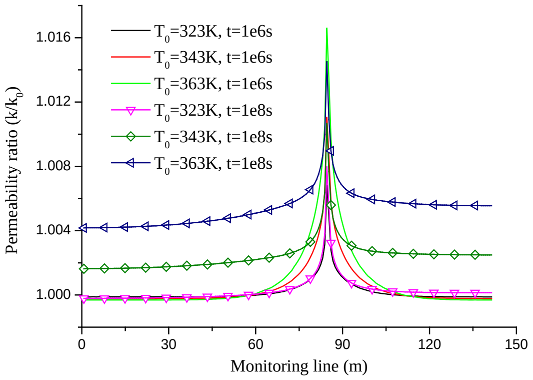


Fig. 4. Distribution of permeability ratio at different cases.

Temperature has a significant influence on the porosity and permeability. Fig. 4 shows the evolution law of permeability under the condition of temperature. The initial permeability is 1×10^{-18} m^2 before drilling. Due to pressure drop, the permeability around the borehole increased due to the gas desorption. The permeability of boreholes over 30 meters changes slowly, which shows that borehole extraction has a limited effect on permeability evolution. When the temperature is higher, the permeability is higher. It indicates the high temperature is beneficial to gas extraction.

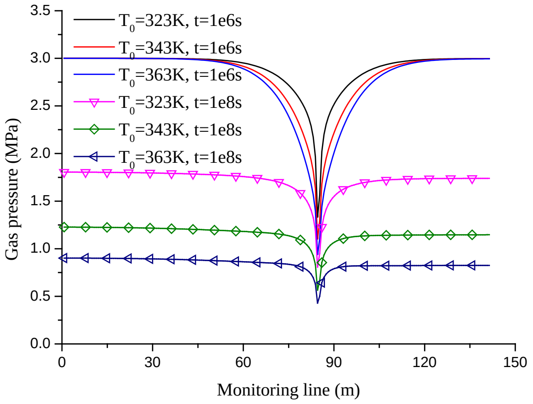


Fig. 5. Distribution of gas pressure at different cases.

A bigger difference can be seen from the distribution of gas pressure. When $t=1\times10^6$ s, the effect of temperature is more obvious around the borehole, but the difference of pressure distribution is not obvious when the distance is far. When $t=1\times10^8$ s, the difference of pressure distribution is very obvious. Temperature affects the gas adsorption, and then affects the distribution of gas pressure. The gas pressure maximum is 1.8 MPa and 0.9 MPa when the temperature is 323K and 363K respectively.

Conclusions

The temperature has a significant impact on the coal seam gas extraction. A fully coupled model is established in this study, which takes into account the coal-gas interaction characteristic. The numerical result shows that high temperature accelerates the gas flow, which is beneficial to the extraction of coal seam. The temperature maximum gradually decreases from 363K to 319 K at production time from 1×10^6 s to 1×10^8 s. Temperature affects the gas adsorption, and then affects the distribution of gas pressure. The gas pressure maximum is 1.8 MPa and 0.9 MPa when the temperature is 323K and 363K respectively.

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Nomenclature

E - young's modulus of coal, [MPa]
E_s - young's modulus of the coal grains, [MPa]
k_0 - initial permeability, [m^2]
P_L - Langmuir pressure constant, [MPa]
V_L - Langmuir volume constant, [m^3/kg]
T - initial coal temperature, [K]

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