A NUMERICAL SIMULATION ON COAL SEAM GAS RECOVERY FROM HIGH TEMPERATURE RESERVOIR

by

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The coal seam gas recovery in deep reservoirs often meets high temperature. The change of temperature can greatly influence gas sorption, and couples heat transfer with coal deformation and gas-flow. This paper modifies the conventional Langmuir adsorption equation into a non-isothermal adsorption equation with a set of experimental data. After then, a fully coupled thermo-hydro-mechanical model of coal deformation, gas-flow and heat transfer is established. By using a finite element approach of COMSOL multi-physics, a numerical simulation of coal seam gas recovery from high temperature reservoir is subsequently implemented. The results show that the gas pressure and temperature decrease with production time and increase with the distance from production well, the reservoir permeability decreases with production time due to the compaction of increasing effective stress to coal fracture network, the cumulative gas production increases with production time exponentially whereas the production efficiency decreases negative exponentially, that the gas production in earlier 10 years accounts for 80% of the total production in 30 years. Our fully coupled thermo-hydro-mechanical model can improve the current understanding of coal seam gas recovery from high temperature reservoirs.

Key words: *coal seam gas recovery, thermo-hydro-mechanical model, gas sorption, variable temperature, numerical simulation*

Introduction

The temperature is a key factor that affects coal-gas interactions in gas recovery, especially in the high temperature reservoirs [1, 2]. Many researchers have reported that the change of temperature may impact the adsorption capacity of coal to gas [3-5]. Zhang *et al.* [6] examined the sorption and desorption characteristics at temperatures of 35 °C, 45 °C and 55 °C, and found that temperature has an enhancement to the desorption behavior. Apart from the decreasing relationship of adsorption capacity with temperature, Pan *et al.* [7] indicated that the coal samples do not show significant differences in coal methane adsorption capacity at high temperatures (*i. e.*, 50 and 70 °C). Baran *et al.* [8] point out that changes in temperature

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in underground coalbeds can influence the sorption balance, resulting in strains in coal strata, which could lead to the desorption of gas and leaks to the ground surface.

Temperature change of gas reservoirs triggers a series of interactions among coal, gas and heat, making gas recovery a fully coupled thermo-hydro-mechanical (THM) problem [9]. Teng *et al.* [10] developed a gas permeability model under coupled THM conditions. Abed *et al.* [11] described a THM framework that suitable for modeling the behavior of unsaturated soils and rock. Gao *et al.* [12] created a theoretical derivation of coupled THM model by using a fully coupled finite element approach. Fan *et al.* [13] explored the fully coupled THN-chemical response of CO_2 enhanced CBM recovery considering the coupling relationships of competitive sorption of binary gas and dissolved gas in water.

The target of the paper is to modify the conventional Langmuir adsorption equation into a non-isothermal adsorption equation with experimental data and to develop a fully coupled THM model. Based on the partial differential solver COMSOL multi-physics, a numerical simulation of coal seam gas recovery from high temperature reservoir is implemented and a series of field analyses are discussed.

Mathematical model

This work is based on the rational continuum mechanics with three main assumptions that: coal is homogeneous, isotropic, porous continuum, coal seam gas is ideal and its flow obeys the Darcy's law, and the effects of temperature on viscosity are ignored.

The Langmuir equation is often introduced to describe the adsorbed gas volume as:

$$V_{sg} = abp(1+bp) \tag{1}$$

where a and b donate the Langmuir volume constant and pressure constant, respectively, and p is the gas pressure.

The adsorption capacity of coal to gas decreases when the temperature of gas reservoir changes. According to our previous work [10], the Langmuir constants, under a variable temperature range of lower than 100 °C, can be modified as:

$$a = a_0 - \lambda T, \quad b = b_0 \exp\left[-\Delta H_{abs}/\left(\mathrm{R}T\right)\right] \approx b_0 \exp\left[-\Delta H_{abs}/\left(\mathrm{R}T_0\right)\right] \tag{2}$$

where a_0 and b_0 are the initial values of variables a and b, R – the universal gas constant, ΔH_{abs} – the adsorption enthalpy, λ – a temperature sensitive coefficient, and T is the coal temperature.

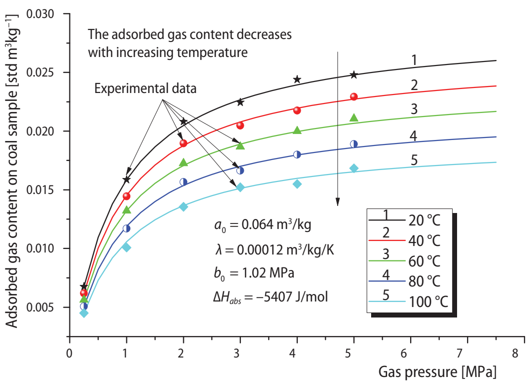

Figure 1. Validation of gas adsorption with experimental data under variable temperature

Figure 1 shows the good matching between the theoretical results (LINE) from the modified Langmuir equation and the experimental data (POINTS). It obviously indicates that the adsorbed coal seam gas content decreases with the increasing temperature.

The gas sorption causes the swell of coal block, described:

$$\varepsilon_s = \alpha_{sg} V_{sg} = \alpha_{sg} abp\left(1+bp\right) \tag{3}$$

where α_{sg} is the coefficient for adsorption induced deformation.

Besides, the change of temperature will induce a volumetric stain, given:

$$\varepsilon_T = \alpha_T \Delta T \tag{4}$$

where α_T donates the thermal expansion coefficient, and $\Delta T = T - T_0$ is the increment of temperature to the initial temperature.

The volumetric strain of coal block is:

$$\varepsilon_v = \varepsilon_T + \varepsilon_s + \frac{\sigma'_{ij}}{K} \tag{5}$$

where $\sigma'_{ij}=\sigma_{ij} + \alpha p$ is the effective stress, K – the bulk modulus of coal, and α – the Biot's coefficients of the coal.

The mechanical equilibrium equation and strain-displacement relation equation are expressed:

$$\sigma_{ij,j} + X_i = 0 \tag{6}$$

$$\varepsilon_{ij} = \frac{u_{i,j} + u_{j,i}}{2} \tag{7}$$

where X_i is the body force.

Combining eqs. (3)-(7), one obtains the modified equilibrium equation for the coal deformation as:

$$Gu_{i,kk} + \frac{Gu_{k,ki}}{1-2v} - \alpha p_i - K\varepsilon_{si} - K\alpha_T T_i + X_i = 0 \tag{8}$$

where the shear modulus and the bulk modulus of coal are $G = 0.5E/(1+v)$ and $K = E/3(1-2v)$, respectively, E – the Young's modulus of coal, and v – the Poisson ratio. The Biot's coefficients of the coal can be repressed as $\alpha = 1 - K/K_s$, where K_s is the grain elastic modulus.

The coal permeability, k, is assumed to vary with coal porosity ϕ as a cubic law as [10]:

$$\left(\frac{k}{k_0}\right) = \left(\frac{\phi}{\phi_0}\right)^3 = \left\{1 - \left(1 - \frac{\alpha}{\phi_0}\right)\left[\left(\varepsilon_v + \frac{p}{K_s} - \varepsilon_s - \varepsilon_T\right) - \left(\varepsilon_{v0} + \frac{p_0}{K_s} - \varepsilon_{s0}\right)\right]\right\}^3 \tag{9}$$

The whole content of the gas in coal reservoir contains the free gas in the coal porosity and the adsorbed gas in coal matrix, given:

$$m_g = \rho_g \phi + \rho_c \rho_{ga} V_{sg} \tag{10}$$

where $\rho_g = M_g p/(\mathrm{R}T)$, M_g – the molar mass of gas, ρ_c – the density of coal, and ρ_{ga} – the density of gas at standard conditions.

Thus, the Darcy flow equation of gas in reservoir is defined [14, 15]:

$$\frac{\partial m_g}{\partial t} + \nabla\left[\rho_g\left(-\frac{k}{\mu}\nabla p\right)\right] = 0 \tag{11}$$

where μ is the dynamic viscosity coefficient of the gas.

Substituting eqs. (1)-(10) into eq. (11), we have:

$$\left\{\left[\frac{\phi}{T}+\frac{(\alpha-\phi_0)p}{K_sT}\right]+\frac{ab}{(1+bp)^2}\left[\frac{\rho_c p_0}{T_0}-\frac{(\alpha-\phi_0)\alpha_{sg}p}{T}\right]\right\}\frac{\partial p}{\partial t}-$$
$$-\left\{\left[\frac{\phi p}{T^2}+\frac{(\alpha-\phi_0)\alpha_T p}{T}\right]+\frac{b\lambda p}{1+bp}\left[\frac{\rho_c p_0}{T_0}-\frac{(\alpha-\phi_0)\alpha_{sg}p}{T}\right]\right\}\frac{\partial T}{\partial t}+$$
$$+\nabla\left[\frac{p}{T}\left(-\frac{k}{\mu}\nabla p\right)\right]+\frac{(\alpha-\phi_0)p}{T}\frac{\partial\varepsilon_v}{\partial t}=0 \tag{12}$$

The energy conservation equation is defined [16]:

$$C_{\text{eq}}\frac{\partial T}{\partial t}+p\nabla\left(-\frac{k}{\mu}\nabla p\right)+K\alpha_T T\frac{\partial\varepsilon_v}{\partial t}=K_{\text{eq}}\nabla^2T+\rho_g C_g\frac{k}{\mu}\nabla p\nabla T \tag{13}$$

where K_{eq} is the effective thermal conductivity and the specific heat capacity of coal is:

$$C_{\text{eq}}=\phi\rho_g C_g+(1-\phi)\rho_c C_c \tag{14}$$

in which, C_g and C_c are the specific heat constants of gas and solid, respectively.

Thus, eqs. (8), (12) and (13) make up a fully coupled THM model that includes coal deformation, gas-flow and heat transfer. The couplings that one affects another among these three fields are illustrated in fig. 2. This mathematical model is applied into a numerical simulation of coal seam gas recovery from high temperature reservoir. Based on the powerful PDE-based modeling environment of COMSOL multi-physics, this simulation is carried out and well solved.

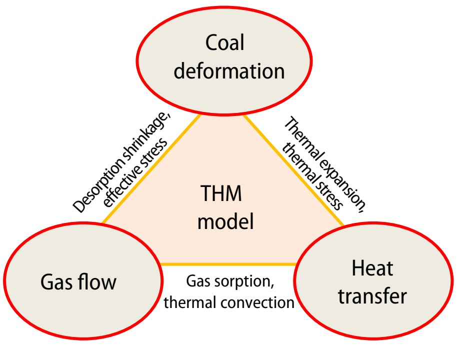

Figure 2. Interactions among THM model

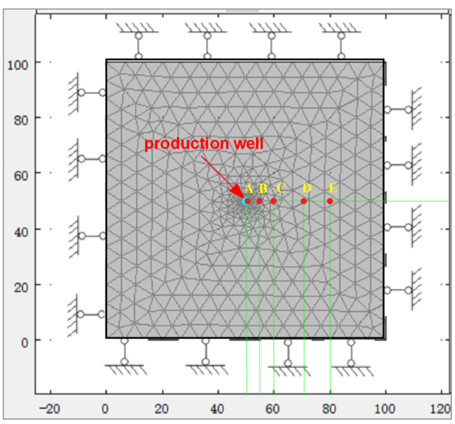

Figure 3. Numerical simulation mode

Numerical simulation on coal seam gas recovery under variable temperature

In order to investigate the gas recovery under variable temperature, a 2-D simulation model for gas production from a high temperature reservoir was constructed in fig. 3. The length and width of the proposed plane strain model are both 100 meters. In the model, a gas production well with a radius of 0.1 m is located at the center.

The initial reservoir gas pressure and temperature are 4.5 MPa and 343 K, respectively. For the field of coal deformation, the normal displacements at the outer boundaries are prescribed, whereas the internal boundary is free. For the fields of gas-flow and heat transfer, the outer boundaries are symmetry, whereas the internal boundary has constant barometric pressure or temperature of 298 K, respectively. To compare the characteristics at different points, five observation points (Point A, B, C, D and E) with different distances (1, 5, 10, 20, 30 m) from the wellbore are pre-set for later analysis.

Modeling results

Evolution of reservoir temperature

Figure 4 is the distribution of reservoir temperature after different production time. It shows that the temperature increases with the distance from heat production well and decreases with the production time. As the heat flows toward the production well, the temperature in areas with shorter distances decreases faster, and heat will not transfer to the further areas unless after a long time. For example, after 5 years, the temperature at observation A is 320 K whereas the temperatures at observation B, C, and D are 338, 342 and 343 K, respectively. However, after 30 years, the temperatures at B, C and D are 333, 336 and 342 K, respectively.

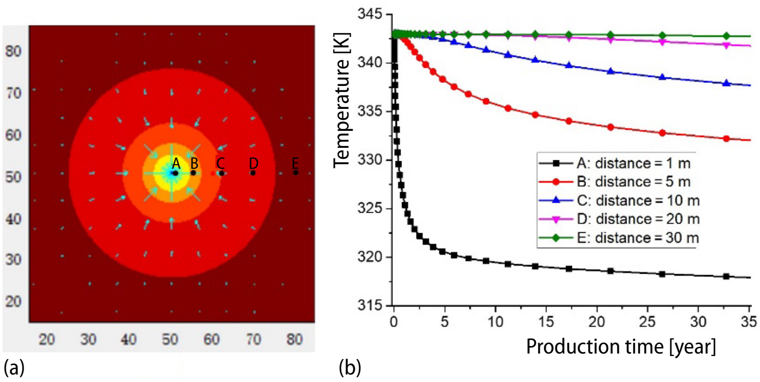

Figure 4. Distribution of reservoir temperature; (a) temperature distribution after 30 years (b) temperature distribution at different distance

Evolution of reservoir gas pressure

Figure 5 shows the evolutions of gas pressure with production time at five observation points and its distributions in the plane space. It distinctly indicates that gas pressures decreases with production time. Moreover, the reservoir gas pressure increases with the distances from

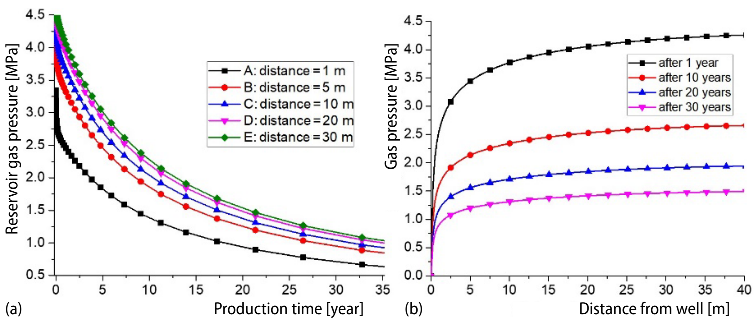

Figure 5. Evolution of gas pressure with production time; (a) pressure evolution with time (b) pressure distribution with distance

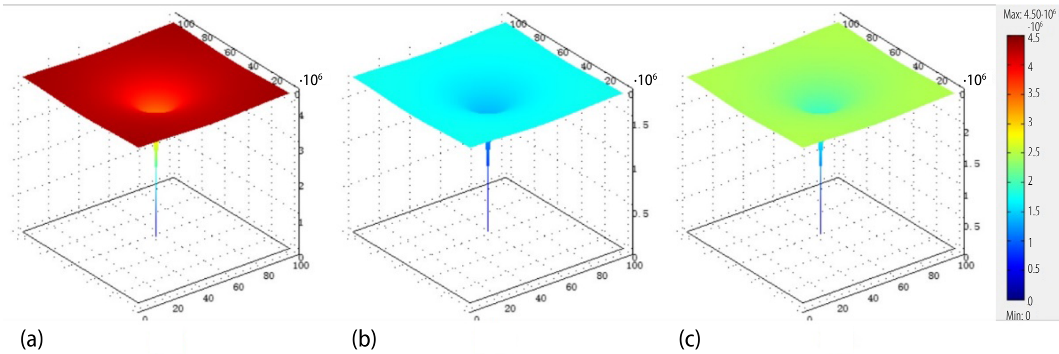

Figure 6. Distribution of gas pressure; (a) after 1 year, (b) after 10 year, and (c) after 20 year

the production well, making a funnel-form distribution that can be seen in fig. 6. It is obvious that the recovery at the production well is quicker that the further areas. From the distributions of gas pressure after production time of 1, 10, and 20 years in figs. 5(b) and 6, one can conclude that the mean gas pressures are about 4, 2.5, and 1.5 MPa after 1, 10, and 20 years, respectively.

Evolution of coal permeability

Figure 7 is the evolutions of normalized coal permeability at observation point B, C, D, E, and the evolutions with production time. Figure 7(a) shows that coal permeability decreases with production time. Taking point C as an example, one can obtain that the normalized coal permeability decreases from 1 to 0.966, 0.957, 0.950, and 0.946 after 5, 10, 20, and 30 years. Figure 7(b) shows that the decreasing distance corresponds to higher permeability ratio. For example, the normalized coal permeability decreases to 0.968, 0.946, 0.934, and 0.927 at point B, C, D and E after 30 years. As the thermal expansion, thermal sorption and effective stress complexly affect coal permeability. Evolutions of coal permeability from fig. 7 indicate that the gas recovery caused increasing of the effective stress compacts the fracture network seriously than the other two components.

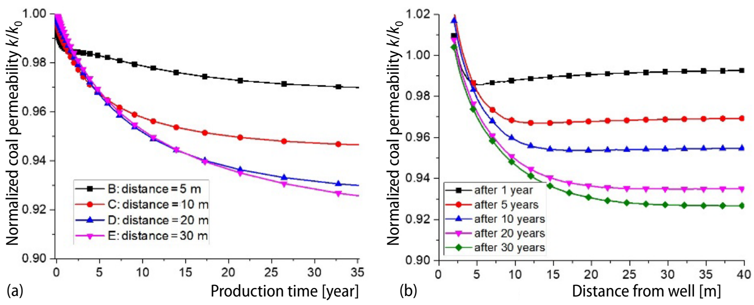

Figure 7. Evolution of coal permeability; (a) permeability evolution with time and (b) permeability distribution with distance

Gas production and efficiency

Figure 8 is the evolution of cumulative gas production and its efficiency with production time. It indicates that the cumulative gas production increases with production time almost exponentially, meanwhile the production efficiency decreases negative exponentially. From the figure, we can find that the cumulative gas content after a production of 30 years is

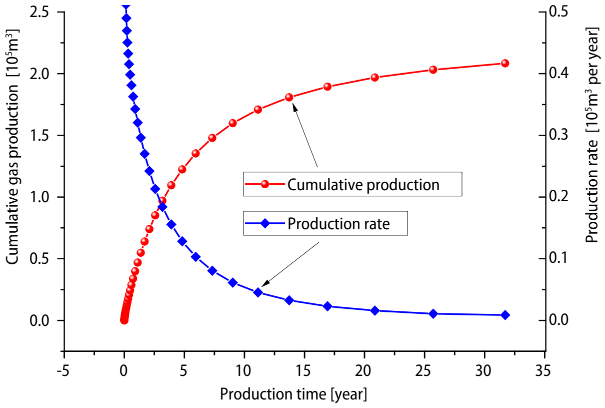

Figure 8. Evolution of gas production

2.06×10^5 m^3 while the cumulative gas content after 10 years is 1.65×10^5 m^3, the production in the earlier 10 years accounts for 80% of total production in 30 years.

Conclusion

This study modified the gas sorption under variable temperature and assembled it into the establishment of a fully coupled THM model that included multi-physics of coal deformation, gas-flow and heat transfer. The coupled model was applied to the modeling and numerical simulation of coal seam gas recovery from high temperature reservoir. The temperature of the gas reservoir decreases with the production time and increases with the distance from the heat production well as the heat flows toward the production well. The reservoir gas pressure increases with the distances from the production well, making a funnel-form distribution. Moreover, the gas pressure decreases with production time. The reservoir permeability decreases with production time due to the compaction of increasing effective stress to coal fracture network. The cumulative gas production increases with production time exponentially while the production efficiency decreases negative exponentially. The fully coupled THM model can improve the current understanding of coal seam gas recovery from high temperature reservoirs.

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Nomenclature

C_c – specific heat capacity of coal, [kJkg^{-1}K^{-1}]
E – coal Young's modulus, [MPa]
ΔH_{abs} – adsorption enthalpy, [Jmol^{-1}]
k_0 – initial coal permeability, [mD]
k – coal permeability, [mD]
m_g – gas content in coal, [kgm^{-3}]
R – universal gas constant, [Jmol^{-1}K^{-1}]
T_0 – initial temperature, [K]
T – -temperature, [K]
V_{sg} – adsorbed gas volume, [m^{3}kg^{-1}]

Greek symbols

α_{sg} – sorption-strain coefficient, [kgm^{-3}]
λ – temperature coefficient, [K^{-1}]
μ – dynamic viscosity coefficient of gas, [Pas]
ρ_c – density of coal, [kgm^{-3}]
ρ_g – density of gas (standard condition), [kgm^{-3}]

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