TEMPERATURE FIELD DISTRIBUTION OF COAL SEAM IN HEAT INJECTION

by

Zhizhen ZHANG [*]***, Weihong PENG, Xiaoji SHANG, Kun WANG, Heng LI, and Wenming MA***

State Key Laboratory for Geomechanics and Deep Underground Engineering,
School of Mechanics and Civil Engineering, China University of Mining and Technology,
Xuzhou, China

Original scientific paper
https://doi.org/10.2298/TSCI17S1039Z

In this article, we present a natural boundary element method (NBEM) to solve the steady heat flow problem with heat sources in a coal seam. The boundary integral equation is derived to obtain the temperature filed distribution of the coal seam under the different injecting conditions.

Key words: *steady heat conduction, coal seam, heat injection, temperature field, natural boundary element method*

Introduction

The coal-bed methane is an unconventional natural gas occurred within coal, which is one of important clean energies and high-quality chemical materials [1]. It is mainly composed of CH_4, generally about 95%, and N_2, CO_2 and other substances [2]. China's potentials in coal-bed methane are very huge, and ranking second in the world, fig. 1, [3]. Coal-bed methane

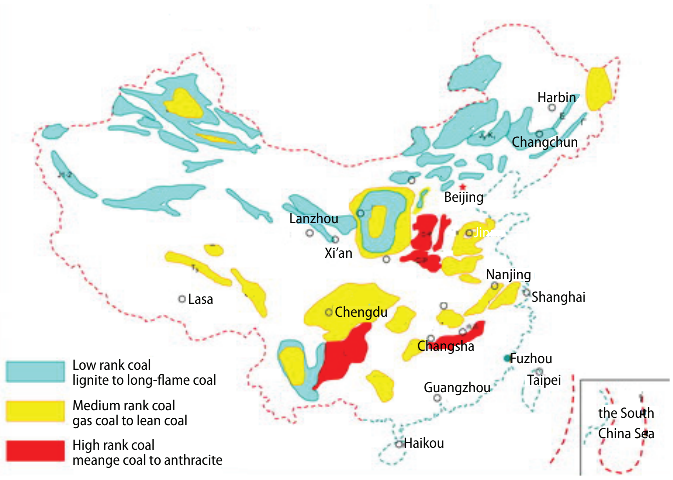

Figure 1. Distribution of coal-bed methane in China
(*for color image see journal web site*)

* Corresponding author, e-mail: zzzcumt@163.com

drainage mining, can fundamentally are adopted to prevent and control coal mine gas accident [4-6], protect the atmospheric environment, and solve the problems of shortages of oil and gas resources in the world [7].

Unlike US, Australia and other coal producing countries, China's coal seams have been very low permeability [8]. It restricts the gas desorption and flow, so the coal-bed methane has not been formed in the industrial scales in China.

Temperature plays an important role in coal fracture, coal-bed methane adsorption, desorption and seepage [9-12]. Laboratory tests and filed investigations showed that increasing temperature of coal seam could improve the coal-bed permeability and enhance the coal-bed gas production effectively. The heat injection is an advanced increasing production technique with a great future potential shown in fig. 2. There are three feasible ways to heat the coal seam, *i. e.* injecting high temperature steam, burning coal body and direct current heating. No matter what kind of technology, the most important thing is to predict the temperature filed distribution of the coal seam.

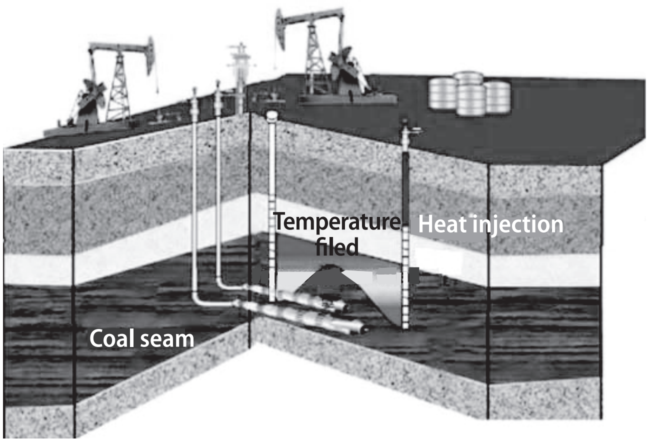

Figure 2. Heat injection technology

In this paper, our aim is to present a natural boundary element method (NBEM) to solve the steady heat flow problem with the heat sources in a coal seam.

Two production-increasing mechanisms of the injection

There are two production-increasing mechanisms of heat injection.

(1) Coal-bed gases exist in the forms of free gas, adsorbed gas on coal surface, and adsorbed gas in coal matrix, fig. 3. After injecting high temperature steam, a large amount of heat is diffused into the coal seam, which increases the temperature of the coal body. The methane

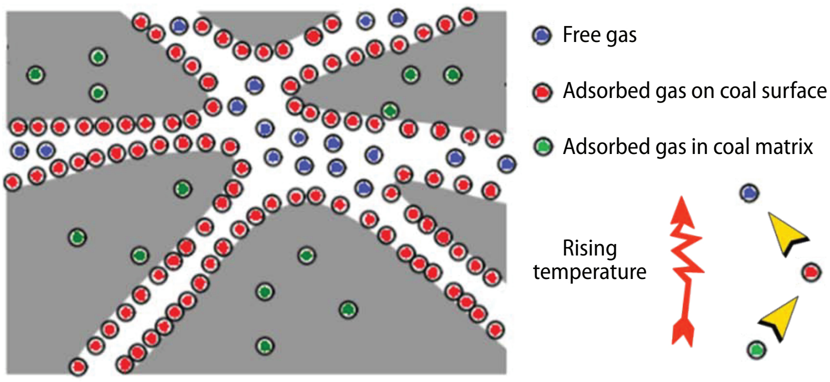

Figure 3. High temperature enhances the desorption capacity of gas molecules
(*for color image see journal web site*)

molecules in the coal seam absorb heat. Their kinetic energy increases, and the thermal motion becomes intense, which make them released from the coal matrix and surface to the free gas. High temperature can enhance the desorption capacity of methane molecules, and increase the rate of desorption at the same time.

Desorbed coal-bed methane diffuses outward to the fractures through the coal matrix and pores. In this process, the coal-bed methane absorbs quantity of heat to increase its intrinsic energy. The increase of a large number of desorbed gas molecules leads to the gas concentration. More coal-bed methane diffuses into the fracture network, and the gas pressure increases in the effect of the concentration gradient.

(2) When the high temperature steam is injected into the coal seam, the crack is initiated, expanded and connected by the gas pressure. At the same time, thermal fracture will also be produced by the high temperature. The thermal cracking can provide the channels for the high temperature water-gas mixture, which would promote the further fracturing of the coal. Coupled with the role of the stress field, coal seam cracks connect each other to form the complex fracture network, thereby changing the coal seam permeability. The gas production would be enhanced in the temperature, stress and seepage fields in the coupling effect.

The MTS816 rock test system and heat injection system were used to study the evolution of the fractures in lignite under three cases, *i. e.* water injection, gas injection and high temperature steam injection, fig. 4. The results show that more fractures are produced under the high temperature injection. When water is injecting, a large fissure is generated, and the micro-cracks are less in the coal body. Under gas injecting situation, the coal produced two macro cross-cracks, and micro-cracks become more relatively. Contrastingly, high temperature steam could make the coal produced the most cracks, and form a complex fracture network system.

Field test was also conducted in China Pingdingshan Group, the results show the mixed gas flow increased from 0.0015 m^3/min to 0.179 m^3/min after heat injection, while methane gas flow went up from 0.0015 m^3/min to 0.023 m^3/min, an increase of 13.3 times, see fig. 5.

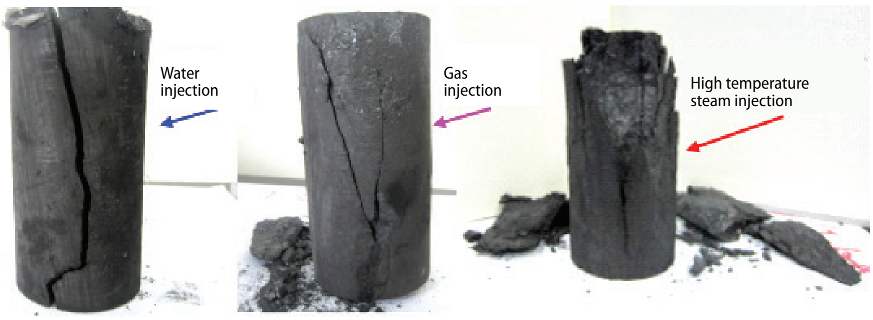

Figure 4. Fractures in lignite under water injection, gas injection and high temperature steam injection

Temperature filed distribution of coal seam under different injecting conditions

In order to evaluate the effect of heat injection on the gas production enhancement, the temperature distribution of the coal seam must be predicted. According to the engineering investigation, it can be simplified as the thermal conduction in steady state of heating sources. The two-dimensional model for the first-class boundary condition to investigate the heat conduction process inside the coal seam with heat injection can be given as [13, 14]:

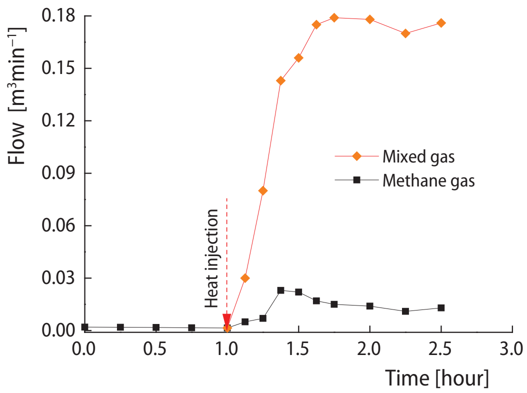

Figure 5. Gas flow change after the heat injection in a coal seam

$$\begin{cases} -\nabla^2 T = f \\ T\big|_\Gamma = T_0 \end{cases} \tag{1}$$

where T is the temperature in coal seam, f – the strength of heat source power W divided by the thermal conductivity λ of coal given by $f = W/\lambda$, and T_0 is the temperature of the heat source on the surface Γ in injection holes.

According to Fourier series, NBEM can be applied to the Dirichlet boundary problem. If we find a specific solution ω, eq. (1) is equivalent to the following equation [15, 16]:

$$\begin{cases} -\nabla^2 u = 0 \\ u\big|_\Gamma = T_0 - \omega_0 \end{cases} \tag{2}$$

where $u = T - \omega$, and ω_0 is the boundary value of ω on Γ.

Based on the complex variable method, the real and imaginary parts of any analytic function are the solutions of the harmonic equation. Power function is a kind of analytic function, so we have:

$$\omega = (x + \mathrm{i}y)^n = r^n \exp(\mathrm{i}n\varphi) \tag{3}$$

where $r,\ \varphi \in \Omega$.

From eq. (3), $\mathrm{Re}(\omega) = r^n \cos n\varphi$ and $\mathrm{Im}(\omega) = r^n \sin n\varphi$ are both solutions of the harmonic equation, so any linear combination is also its solution, which is expressed as [17]:

$$u(r,\varphi) = \sum_{n=0}^{\infty} (a_n \cos n\varphi + b_n \sin n\varphi) r^n \tag{4}$$

where $r,\ \varphi \in \Omega$.

The general solution of the harmonic equation in plane polar co-ordinates system has a form of variables separation given as [17]:

$$u(r,\varphi) = C_0 + D_0 \ln(r) + \sum_{n=1}^{\infty} (A_n \cos n\varphi + B_n \sin n\varphi)(C_n r^n + D_n r^{-n}) \tag{5}$$

where $r, \varphi \in \Omega$, and C_0, D_0, A_n, B_n, C_n, D_n are all undetermined coefficients.

Equation (5) can be given in the series form [17]:

$$u(r,\theta) = D_0 \ln(r) + \sum_{-\infty}^{\infty} a_n r^{|n|} \mathrm{e}^{\mathrm{i}n\theta} \tag{6}$$

In a circle area, $D_0 \ln(r)$ does not exist. Thus, the general solution in unit circle is expressed as:

$$u(\theta) = u(1,\theta) = \sum_{-\infty}^{\infty} a_n \mathrm{e}^{\mathrm{i}n\theta} \tag{7}$$

Suppose that $u = pu_0$ and $p = \sum_{-\infty}^{\infty} p_n \mathrm{e}^{\mathrm{i}n\theta}$, then we get $a_n r^{|n|} = 2\pi p_n a_n$.
Thus, we have:

$$\begin{aligned} p &= \sum_{-\infty}^{\infty} \frac{1}{2\pi} r^{|n|} \mathrm{e}^{\mathrm{i}n\theta} = \\ &= \frac{1}{2\pi} \frac{1}{1 - r\mathrm{e}^{\mathrm{i}\theta}} + \frac{r\mathrm{e}^{-\mathrm{i}\theta}}{1 - r\mathrm{e}^{-\mathrm{i}\theta}} = \qquad (0 \le r < 1) \\ &= \frac{1 - r^2}{2\pi(1 + r^2 - 2r\cos\theta)} \end{aligned} \tag{8}$$

From eqs. (7)-(8), we have the boundary integral equation of the harmonic equation in unit circle, which is given:

$$u(r,\theta) = \frac{1}{2\pi} \int_0^{2\pi} \frac{(1 - r^2) u(1,\theta')}{1 + r^2 - 2r\cos(\theta - \theta')} \mathrm{d}\theta', \quad (0 \le r < 1) \tag{9}$$

Generalize eq. (9) to the circle area of radius *R*. We get the boundary integral equation of eq. (2) in the form:

$$u(r,\theta) = \frac{R^2 - r^2}{2\pi} \int_0^{2\pi} \frac{u_0(\theta')}{R^2 + r^2 - 2Rr\cos(\theta - \theta')} \mathrm{d}\theta', \quad (0 \le r < R) \tag{10}$$

Because

$$\omega = \iint_{\Omega} G(r,\theta,r',\theta') f(r',\theta') \mathrm{d}r' \mathrm{d}\theta'$$

is a particular solution of eq. (1) [17], we finally get the solution of the heat conduction in a coal seam under the heat injection:

$$\begin{aligned} T(r,\theta) &= u(r,\theta) + \omega = \\ &= \frac{R^2 - r^2}{2\pi} \int_0^{2\pi} \frac{u_0(\theta')}{R^2 + r^2 - 2Rr\cos(\theta - \theta')} \mathrm{d}\theta' + \iint_{\Omega} G(r,\theta,r',\theta') f(r',\theta') \mathrm{d}r' \mathrm{d}\theta' \end{aligned} \tag{11}$$

where $G(r,\theta,r',\theta')$ is the Green function (GF), which was given:

$$G(r,\theta,r',\theta') = \frac{1}{4\pi} \ln\left(\frac{R^4 + r^2 r'^2 - 2R^2 r r' \cos\theta}{R^2 r^2 + R^2 r'^2 - 2R^2 r r' \cos\theta} \right) \tag{12}$$

Making use of eqs. (10) and (11), we can obtain the temperature distribution of the coal seam under different injecting conditions shown in fig. 6.

Efficiency evaluation of heat injection

When the high temperature steam is injected into the coal seam, the heat is absorbed by the coal-bed gas molecules in the heating zone, see fig. 7. The molecular activity and kinetic energy increase. A large amount of gas molecules are desorbed from the coal matrix and fracture surface. The energy dissipation at the front of the heating zone is absorbed by the coal-bed methane and becomes the power of the coal-bed methane desorption. The desorption rate of the coal-bed methane decreases with the diffusion radius of the heat zone. The coal-bed methane is

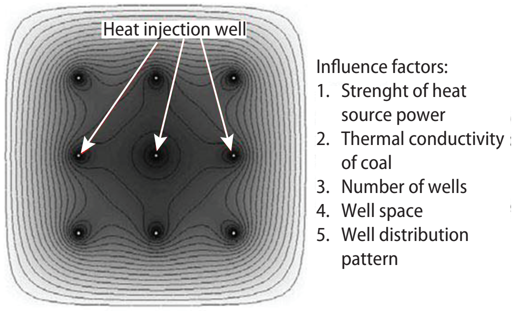

Figure 6. Influencing factors on the temperature distribution of a coal seam

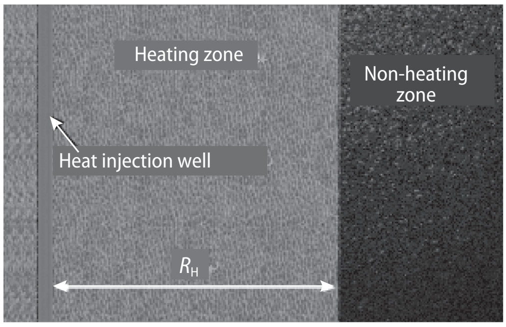

Figure 7. Heating and non-heating zones in the coal seam under the heat injection

continuously desorbed from the coal seam and the gas concentration is increased and diffused into the coal fissure under the effect of the concentration gradient. In the non-heating zone, the coal-bed methane temperature does not change, and the rate of desorption remains unchanged.

The heat in desorption of the coal and coal-bed methane in the heating zone can be expressed as:

$$Q_\mathrm{d} = \int_0^{R_H}\int_0^{2\pi}\left[\left(1-f_g\right)\rho_c C_c + \frac{f_g \rho_g C_g}{M_g}\right]\left[T(r,\theta)-T_0\right]A\mathrm{d}r\,\mathrm{d}\theta \tag{13}$$

where R_H is the radius of the heating zone, f_g – the quality fraction of coal-bed methane in coal seam, M_g – the molar mass of coal bed methane, A – the area of the coal-bed methane desorption, and ρ_c, C_c, ρ_g, and C_g are density and specific heat of coal and gas, respectively.

The efficiency of heat injection is given by:

$$\eta = \frac{Q_\mathrm{d}}{Q_{in}} \tag{14}$$

where Q_{in} is the total injecting heat, η – the efficiency of heat injection, and Q_d – the heat in desorption of the coal and coal-bed methane.

Conclusion

In our work, we addressed two production-increasing mechanisms of the heat injection. With the help of NBEM, we handled the heat flow problem with heat sources in a coal seam. Enhancing the desorption capacity of methane molecules and thermal cracking are two major mechanisms for promoting the gas extraction under the heat injection. The boundary integral equation is proposed to obtain the temperature distribution of the coal seam in different injecting conditions. The efficiency of the heat injection was also suggested.

Acknowledgment

This work is provided by the Fundamental Research Funds for the Central Universities (No. 2017QNA31), and a Project Funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD2014).

Nomenclature

A – area of coal-bed methane desorption, [m^2]
C_c – specific heat of coal, [Jmol^{-1}K^{-1}]
C_g – specific heat of gas, [Jmol^{-1}K^{-1}]
M_g – molar mass of coal-bed methane, [kgmol^{-1}]
R_H – radius of the heating zone, [m]
T – temperature, [°C] T_0 – injecting temperature, [°C]
W – strength of heat source power, [Wm^{-3}]

Greek symbols

λ – thermal conductivity, [Wm^{-1}°C^{-1}]
ρ_c – density of coal, [kgm^{-3}]
ρ_g – density of gas, [kgm^{-3}]

References

[1] Squarek, J., Dawson, M., Coalbed Methane: Promise and Practise, *Oil & Gas Journal*, *104* (2006), 28, pp. 37-38
[2] Zhou F, *et al.*, Recent Developments in Coal Mine Methane Extraction and Utilization in China: A Review, *Journal of Natural Gas Science & Engineering*, *31* (2016), Apr., pp. 437-458
[3] Yao, Y. B., *et al.*, A Comprehensive Model for Evaluating Coalbed Methane Reservoirs in China, *Acta Geologica Sinica*, *82* (2008), 6, pp. 1253-1270
[4] Xue, Y., *et al.*, Thermo-Hydro-Mechanical Coupled Mathematical Model for Controlling the Pre-Mining Coal Seam Gas Extraction with Slotted Boreholes, *International Journal of Mining Science and Technology*, *27* (2017), 3, pp. 473-479
[5] Geng, J. B., *et al.*, Regression Analysis of Major Parameters Affecting the Intensity of Coal and Gas Outbursts in Laboratory, *International Journal of Mining Science and Technology*, *27* (2017), 2, pp. 327-332
[6] Qi, L. L., *et al.*, Pore Characterization of Different Types of Coal from Coal and Gas Outburst Disaster Sites Using Low Temperature Nitrogen Adsorption Approach, *International Journal of Mining Science and Technology*, *27* (2017), 2, pp. 371-377
[7] Aguilera, R. F., *et al.*, Link between Endowments, Economics and Environment in Conventional and Unconventional Gas Reservoirs, *Fuel*, *126* (2014), 9, pp. 224-238
[8] Xu, J. Z., *et al.*, Mechanism and Application of Pulse Hydraulic Fracturing in Improving Drainage of Coalbed Methane, *Journal of Natural Gas Science and Engineering*, *40* (2017), Apr., pp.79-90
[9] Wang, K., *et al.*, Investigation of Gas Pressure and Temperature Effects on the Permeability and Steady-State Time of Chinese Anthracite Coal: An Experimental Study, *Journal of Natural Gas Science and Engineering*, *40* (2017), Apr., pp. 179-188
[10] Zhang, Z. Z., *et al.*, Effect of Thermal Treatment on Fractals in Acoustic Emission of Rock Material, *Advances in Materials Science and Engineering*, *2016* (2016), ID 6309856
[11] Zhou, F. D., *et al.*, Injecting Pure N-2 and CO_2 to Coal for Enhanced Coalbed Methane: Experimental Observations and Numerical Simulation, *International Journal of Coal Geology*, *116-117* (2013), 5, pp. 53-62
[12] Zhang, Z. Z., Fractal Dimension of Fracture Surface in Rock Material after High Temperature, *Advances in Materials Science and Engineering*, *2015* (2015), ID 468370
[13] Yang, X. J., A New Integral Transform Method for Solving Steady Heat-transfer Problem, *Thermal Science*, *20* (2016), Suppl. 3, pp. S639-S642
[14] Yang, X. J., A New Integral Transform Operator for Solving the Heat-Diffusion Problem, *Applied Mathematics Letters*, *64* (2017), Feb., pp. 193-197
[15] Yang, X. J., A New Integral Transform with an Application in Heat-Transfer Problem, *Thermal Science*, *20* (2016), Suppl. 3, pp. S677-S681
[16] Yang, X. J., Gao, F., A New Technology for Solving Diffusion and Heat Equations, *Thermal Science*, *21* (2017), 1, pp.133-140
[17] Yu, D. H., *Mathematical Theory of the Natural Boundary Element Method* (in Chinese), Science Press, Beijing, 1993

Paper submitted: March 10, 2017
Paper revised: May 1, 2017
Paper accepted: May 10, 2017