NUMERICAL SIMULATION OF DAMAGE AND PERMEABILITY EVOLUTION MECHANISM OF COAL SEAM UNDER MICROWAVE RADIATION

by

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Original scientific paper
https://doi.org/10.2298/TSCI180512133X

Microwave heating is an effective method to improve the recovery rate of coalbed CH_4. In this study, a fully coupled electromagnetic thermodynamic model was developed to study the effects of coal compaction, thermal expansion and thermal gas desorption on coal deformation. The simulation results show that although in the initial stage, the decrease of gas pressure by microwave is not obvious, the distribution of gas pressure in coal seam is obviously affected by microwave after a period of time. The microwave can also affect the mineral composition of rocks, cause rock damage, promote the development of cracks, and promote the increase of permeability.

Key words: *microwave heating*, *coupled model, gas desorption*, *thermal-damage, partial differential equations*

Introduction

Coalbed CH_4 is an important clean energy source. In the process of coalbed CH_4 extraction, heat injection may stimulate the gas desorption and gas diffusion. Heating can improve well production by increasing gas diffusivity [1, 2]. Different heating technologies, such as electric heater, hot water drive, high temperature steam, in-situ combustion, and electromagnetic heating (microwave/radio), are suitable for oil and gas industries, respectively [3, 4].

Microwave heating is a reasonable alternative to stimulation gas extraction. Microwave is an electromagnetic radiation that can be transmitted, reflected or absorbed by materials [5-7]. Friction between rapidly rotating molecules causes heat [8]. The evolution of pore structure in microwave heating shows that the specific surface area of irradiated coal decreases, while the average pore size and total pore volume increase [9]. In addition microwave heating, microwave can also affect different mineral compositions of rocks and the rocks will be damaged under microwave irradiation [10, 11]. Therefore, it is proposed that microwave irradiation can be used to assist rock breaking during underground tunneling. Although physical exper-

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iments can directly characterize microwave heating, it is difficult to predict electromagnetic waves and heat transfer in materials. In recent years, coupled electromagnetic-thermal modelling has become a promising tool for quantifying and visualizing microwave heating.

In this study, a fully coupled electromagnetic-thermo-mechanical model was proposed to study the gas interaction during microwave heating, and D-P preparation was used to judge the failure of coal rock. Finally, the sensitivity of microwave heating to permeability and gas pressure is quantitatively evaluated to better understand the gas interaction under microwave heating. The research results can provide scientific guidance for microwave-assisted coalbed CH_4 recovery.

Equations of coupled model

To solve for time-harmonic electromagnetic field distributions, the frequency domain approach can be used to simplify the Maxwell's equations to the Helmholtz vector equation [12]:

$$\nabla \mu_r^{-1}\left(\nabla E\right) - k_0^2\left(\varepsilon_r - \frac{j\sigma}{\omega\varepsilon_0}\right)E = 0 \tag{1}$$

where E is the electric field intensity, μ_r – the relative permeability, k_0 – the free space wave number, and σ – the electrical conductivity.

Darcy flow is often used in the gas migration process. It can be expressed:

$$-\nabla p_f = \frac{\mu}{k_g}\vec{\text{v}} \tag{2}$$

where p_f is the gas pressure, $\vec{\text{v}}$ – the gas velocity vector, μ – the gas dynamic viscosity, ρ_g – the density, and k_g – the permeability.

The flow of gas in the coal satisfies the mass conservation law:

$$\frac{\partial m}{\partial t} + \nabla(\rho_g \vec{\text{v}}) = Q_s \tag{3}$$

where ρ_g is the density of gas, Q_s – the gas source by injection, and t – the real time. This mass content m is defined:

$$m = \rho_{ga}\rho_c V_{sg} + \rho_g \phi \tag{4}$$

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

The general porosity model is defined:

$$\Delta\phi = \frac{1}{K}(\alpha - \phi)(\bar{\sigma} + p) \tag{5}$$

The initial pressure is ρ_0 and the initial porosity is ϕ_0The porosity is expressed:

$$\phi = \frac{1}{1+S}[(1+S_0)\phi_0 + \alpha(S - S_0)] \tag{6}$$

where $S = \varepsilon_V + p / K_s - \varepsilon_s - \alpha_T T$ and $S = \varepsilon_V + p_0 / K_s - \varepsilon_s - \alpha_T T$.

The evolution model of apparent permeability can be obtained:

$$\frac{k_g}{k_{\infty 0}} = \frac{k_\infty}{k_{\infty 0}} = \left(\frac{\phi}{\phi_0}\right)^3 \tag{7}$$

The stress-strain relationships for coal seam can be written:

$$\Delta\varepsilon_{ij} = \frac{1}{2G}\Delta\sigma_{ij} - \left(\frac{1}{6G} - \frac{1}{9K}\right)\Delta\sigma_{kk}\delta_{ij} + \frac{\alpha}{3K}\Delta p\delta_{ij} + \frac{\Delta\varepsilon_s}{3}\delta_{ij} + \frac{\alpha_T}{3}\Delta T\delta_{ij} \tag{8}$$

where ε_{ij} is the strain tensor, σ_{ij} – the stress tensor, ε_s – the sorption-induced volumetric strain, K – the bulk modulus, G – the shear modulus, p – the gas pressure, T – the temperature, δ_{ij} – the Kronecker delta, and α – the biot coefficient.

The volume strain of coal is:

$$\varepsilon_V = \frac{1}{K}(\bar{\sigma} + \alpha p) + \alpha_T T + \varepsilon_s \tag{9}$$

where $\varepsilon_V = \varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33}$ is the volumetric strain, $\bar{\sigma} = \sigma_{kk}/3$ is the mean stress, and the effective stress is defined as $\sigma_{eij} = \sigma_{ij} + \alpha p\delta_{ij}$.

Ignoring the thermal-filtration effect, the total heat flux q_T is expressed:

$$q_T = -\lambda_M \nabla T + \rho_g C_g q_g (T_{ar} + T) \tag{10}$$

where q_T is thermal flux, ρ_s – the gas density, C_g – the gas specific heat constants, and q_g – the Darcy velocity. $\lambda_M = (1-\phi)\lambda_s + \phi\lambda_g$, λ_M, λ_s, and λ_g are the thermal conductivities of coal, solid components and gas components, respectively.

Ignoring the interconvertibility of thermal and mechanical energy, the thermal balance can be expressed:

$$C_{\text{eq}}\frac{\partial T}{\partial t} + K_g\alpha_T T\nabla\left(\frac{K}{\mu}\nabla p_f\right) + K\alpha_T T\frac{\partial\varepsilon_v}{\partial t} = \nabla(k_{\text{eq}}\nabla T) + \rho_{gf}C_g\frac{K}{\mu}\nabla p_f \nabla T + Q_b \tag{11}$$

where T is the temperature, p_f and ρ_{gf} are the pressure and density of gas in natural fractures, respectively, ε_v – the volumetric strain, K – the permeability tensor of natural fractures, μ – the dynamic viscosity of gas, K – the volumetric modulus, C_{eq} and k_{eq} are the equivalent heat capacity and equivalent thermal conductivity.

The Drucker-Prager yield criterion is chosen for the failure criterion of the coal mass:

$$F = \sqrt{J_2} + \alpha_{DP} I_1 - k_{DP} \tag{12}$$

where I_1 represents the first stress invariant, J_2 represents the second deviator stress invariant, and α_{DP} and k_{DP} are related to the cohesion C and friction angle ϕ.

The fully coupled electromagnetic-thermo-hydro-mechanical model is defined by previous field equations. A finite element program is implemented within the framework of COMSOL Multiphysics (the non-linear PDE solver) to solve the fully coupling processes.

Model establishment and numerical simulation

Model establishment

In order to analyze the effect of damage on gas-flow in coal seam, a gas extraction model is established, as shown in the fig. 1. The model is 20 meters long and 20 meters wide. The center of the left boundary and right boundary of the model is two gas extraction boreholes, and it is also the

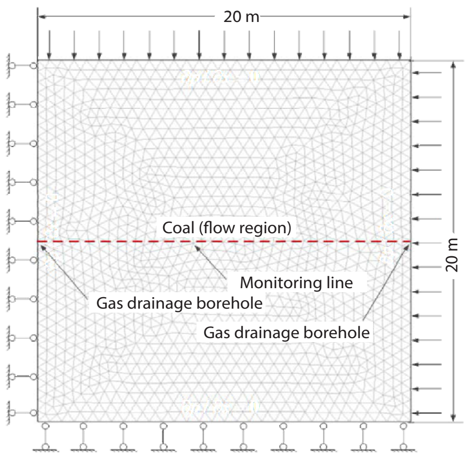

Figure 1. Computational model geometry

location of the electromagnetic wave. The left and lower boundaries of the model constrain the normal displacement, while the right and upper boundaries impose constant loads. The gas extraction pressure is 0.1 MPa. The changes of gas pressure and gas content on the monitoring line are mainly investigated.

Effect of microwave heating on permeability

The rock around the borehole is damaged and destroyed under the action of electromagnetic wave, and the porosity and permeability of coal seam increases under the action of microwave heating. As can be seen from fig. 2, with the continuous action of microwave and the increase of gas extraction time, the permeability of coal seam continues to increase. Figures 3 and 4 show the distribution of gas pressure on coal seam monitoring line under different initial gas pressure conditions. It can be seen from the figure that the difference of gas pressure distribution between different initial gas pressures is not obvious. With the continuation of electromagnetic wave, the permeability of the area around the borehole increases obviously. With the increase of extraction time, the gas content of the whole coal seam decreases, the porosity of the coal seam increases and the permeability increases.

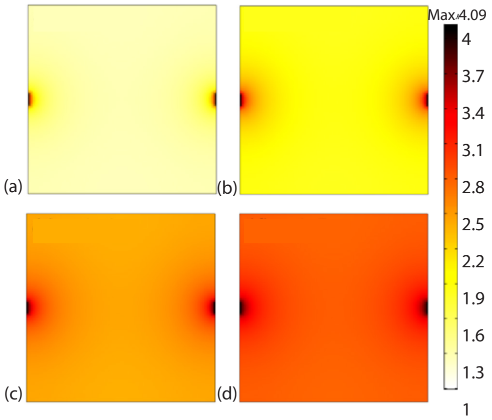

Figure 2. Evolution of permeability ratio in the coal seam; (a) *t* = 1e4 s, (b) *t* = 1e5 s, (c) *t* = 1e6 s, and (d) *t* = 1e7 s

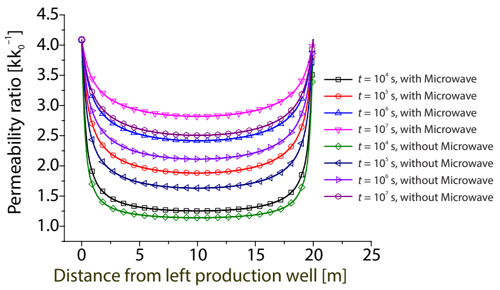

Figure 3. Permeability distribution in the coalbed with the initial pressure 1.45 MPa

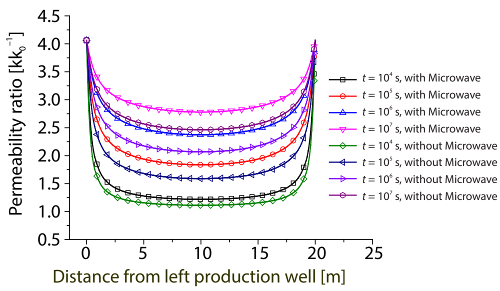

Figure 4. Permeability distribution in the coalbed with the initial pressure 1.79 MPa

With the increase of extraction time, the gas content in coal seam decreases continuously. Especially in the area around drilling holes, the gas adsorption capacity decreases dramatically. The porosity of coal seam decreases continuously, and the porosity increases continuously. It also shows that the effect of microwave heating on permeability. The microwave can also affect the mineral composition of rocks, cause rock damage, promote the development of cracks, and promote the increase of permeability. Gas in coal seam is continuously flowing out into boreholes. There exists the pressure difference between gas pressure in coal seam matrix and gas pressure in cracks. Gas in coal matrix is continuously desorbed and diffused into cracks, resulting in the continuous decrease of gas content in coal seam. The porosity and permeability of coal seam are obviously improved by microwave heating and destruction of coal. In the area near the borehole, the permeability ratio increases to 4.08. After 10^7 seconds, the permeability ratio increases to 2.82 at the center of the coal seam, and while permeability ratio increases 2.51 at the center of the coal seam without microwave.

Effect of microwave heating on gas pressure

Because of the effect of microwave, the temperature of coal seam increases, especially the temperature of coal rock around boreholes firstly. The temperature promotes the increase of porosity and permeability, and increases the desorption and migration of gas in coal seam, which is conducive to gas extraction. As can be seen from fig. 5, with the increase of gas extraction time, the area of low gas pressure in coal seam is expanding. Figures 6 and 7 show the gas pressure distribution on the coal seam monitoring line after different time. Under different initial pressure conditions, the distribution of gas pressure in coal seam is not obvious. In contrast, the difference between microwave and non-microwave on coal seam permeability is more obvious.

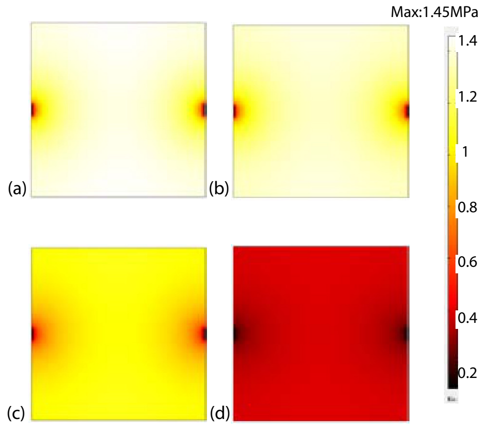

Figure 5. Evolution of gas pressure in the coal seam; (a) *t* = 1e4 s, (b) *t* = 1e5 s, (c) *t* = 1e6 s, and (d) *t* = 1e7 s

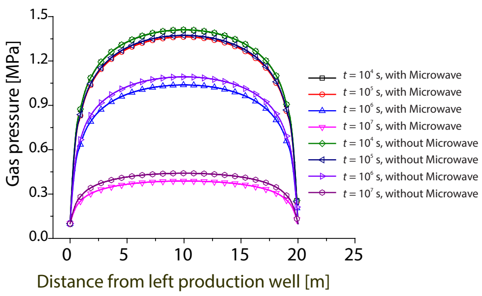

Figure 6. Gas pressure distribution in the coalbed with the initial pressure 1.45 MPa

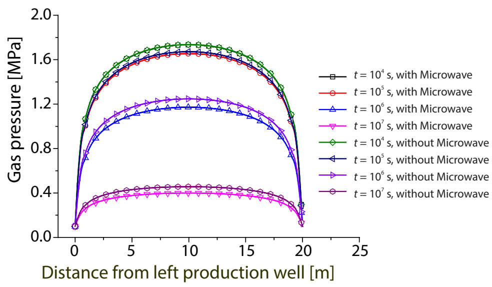

Figure 7. Gas pressure distribution in the coalbed with the initial pressure 1.79 MPa

With the development of microwave, the decreasing range of gas pressure increases. It is also caused due to the increase of permeability, which significantly improves the gas migration in coal seams. At the same time, the damage and damage caused by microwave can also improve the permeability of coal around boreholes. Although in the initial stage, the decrease of gas pressure by microwave is not obvious, the distribution of gas pressure in coal seam is obviously affected by microwave after a period of time. In the center of the model, after 10^7 seconds, the pressure of coal seam heated by microwave is 0.38 MPa. Without microwave heating, the pressure of coal seam in the center of the model is 0.44 MPa, which has a obvious difference. This shows the effect of microwave radiation.

Conclusion

Microwave heating has an obvious effect on gas migration in coal seam. A fully coupled electromagnetic-thermo-mechanical model is established in this study, which takes into account the effects of heat and damage. The numerical results show that microwave heating accelerates the gas-flow, which is beneficial to the extraction of coal seam. On the one hand, microwave causes the rock damage, which is conducive to the development of cracks. On the other hand, it increases the temperature of coal seam, which is conducive to the desorption and diffusion of gas. The porosity and permeability of coal seam are obviously improved by microwave heating and destruction of coal. In the area near the borehole, the permeability ratio increases to 4.08. After 10^7 seconds, the permeability ratio increases to 2.82 at the center of the coal seam, and while permeability ratio increases 2.51 at the center of the coal seam without microwave. In the center of the model, after 10^7 seconds, the pressure of coal seam heated by microwave is 0.38 MPa. Without microwave heating, the pressure of coal seam in the center of the model is 0.44 MPa, which has an obvious difference. This shows the effect of microwave radiation.

Acknowledgment

This study is sponsored by the National Natural Science Foundation of China (No. 51679199), the Foundation for Higher Education Key Research Project by Henan Province (No. 19A130001), the China Postdoctoral Science Foundation (No. 2018M633549), the Ph. D. Programs Foundation of Henan Polytechnic University (No. B2018-65), the Special Funds for Public Industry Research Projects of the Ministry of Water Resources (No. 201501034-04 and 201201053-03), the Initiation Fund of Doctor's Research (No. 107-451117008) and the Key Laboratory for Science and Technology Coordination and Innovation Projects of Shaanxi Province (No. 2014SZS15-Z01).

Nomenclature

k_g – permeability of coal, [m^2]

Greek symbols

ϕ_0 – initial porosity, [–]
ϕ – coal porosity, [–]
μ – gas dynamic viscosity, [Nsm^{-2}]

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Paper submitted: May 12, 2018
Paper revised: June 21, 2018
Paper accepted: August 19, 2018