EFFECT OF DAMAGE ON GAS SEEPAGE MECHANISM IN COAL SEAM BASED ON A COUPLED MODEL

by

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Damage has a significant impact on gas migration in coal seam. In this paper, a coupled hydraulic-mechanical-damage model is established, which takes into account the coupling relationship among coal damage, gas seepage and coal deformation. The simulation results show that the damage of coal body has little effect on seepage characteristic in the initial stage, but the influence of damage on gas seepage is increasing with the increase of time. Both the distribution of gas pressure and the gas adsorption content of coal body have a significant change.

Key words: Gas extraction, Hydraulic-mechanical-damage model, Damage, Partial differential equations (PDEs)

Introduction

Coalbed methane resources are increasingly becoming an important global energy source. Coalbed methane production is also important for the safety of coal mine, because coalbed methane is a harmful gas [1,2]. Coalbed methane resources are normally trapped in unconventional reservoirs by adsorbing to coal matrix. Its extraction usually involves generating from the coal cleat. The pressure of coal seam is reduced so that the methane can be desorbed from the coal matrix and flow from the wellbore to the ground [3,4]. But in underground mining of coal seam, excavation disturbance causes a large number of cracks in coal seam, inducing the change of permeability of coal seam and then causing serious impact on gas migration in coal seam. At the same time, the gas flow will also change the pore pressure in the coal seam, and then change the effective stress in the coal seam. And

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the porosity and permeability of the coal body will also change [5,6]. Therefore, it is a complex coupling process.

The coal-gas interaction and damage mechanism has been studied by many scholars [7-11]. Using the particle flow software, Liu et al. numerically analyzed the coal permeability-improving mechanism of the slot crack network and the borehole gas extraction slotted by water jet underground [12]. Liu et al. developed a fractal permeability model that defines coal permeability as a function of effective stress. In this model, coal microstructure is characterized by fractal dimension of pore size, fractal dimension of throat tortuosity and maximum pore size [13]. In this paper, a coupled hydraulic-mechanical-damage model (gas flow, solid deformation and coal damage) is established. Through this finite element model, the effect of damage on coal seam on gas extraction is quantitatively analyzed.

Equations of coupled model

According to the principle of Terzaghi effective stress, the following equation can be obtained [14]

$$\sigma_{ij}^{'} = \sigma_{ij} - \alpha p \delta_{ij} \tag{1}$$

where $\sigma_{ij}^{'}$ is the effective stress, σ_{ij} is the total stress, α is the Biot coefficient of the coal, p is the pore pressure, and δ_{ij} is the Kronecker symbol.

The permeability of coal can be expressed as

$$\frac{k}{k_0} = \exp\left\{ 3\left(\frac{1}{K} - \frac{1}{K_p}\right)[(\sigma - \sigma_0) - (p - p_0)] \right\} \tag{2}$$

The following equation can be obtained [15]

$$k = k_0 e^{-3c_f(\sigma_e - \sigma_{e0})} \tag{3}$$

where k_0 is the initial permeability of coal, c_f is the compression coefficient of fracture, K is the volume modulus of coal, K_p is the volume modulus of coal fractures, and σ_e is the effective stress.

According to the elastic damage theory, the elastic modulus of coal can be expressed as follows:

$$E = (1 - D)E_0 \tag{4}$$

where E_0 is the elastic modulus of undamaged state, and E is the elastic modulus of the unit in the damaged state.

When the coal is damaged, the effect of the damage on the permeability can be described as

$$k = k_0 e^{-3c_f \lambda D(\sigma_e - \sigma_{e0})} \tag{5}$$

where k_0 is the initial permeability, c_f is the compression coefficient of the coal fracture, λ is the influence coefficient of damage to permeability, and σ_e is the effective stress.

The Darcy velocity of gas is expressed as

$$\vec{q}_g = -\frac{k}{\mu} \nabla p \tag{6}$$

where μ_f is the coefficient of dynamic viscosity, and *k* is the permeability of the gas.

The seepage of gas follows the law of conservation of mass:

$$\frac{\partial m}{\partial t} + \nabla(\rho_g \vec{q}_g) = Q_s \tag{7}$$

where m is the unit volume for the gas in the coal, ρ_g is the gas density, $\vec{q}_g$ is the Darcy velocity, Q_m is the source or sink, and *t* is the time variable.

The mass of the gas m is composed of free term and adsorption term, which can be expressed as

$$m = \rho_g \phi + \rho_{ga} \rho_c \frac{V_L p}{p + p_L} \tag{8}$$

where ρ_{ga} is the gas density under the standard condition, ρ_c is the density of the coal, V_L is the Langmuir volume constant, ϕ is the porosity of the coal, and p_L is the Langmuir volume constant.

The continuity equation of gas seepage can be obtained as

$$\frac{M_g}{RT} \frac{\partial}{\partial t} (\frac{\phi p^2}{p_a}) - \frac{M_g k}{RT \mu_f} \nabla[p(\nabla p + \frac{M_g g}{RT} \nabla z)] = Q_m \tag{9}$$

The coal is regarded as a porous medium, and the coal element satisfies the constitutive equation. It can be expressed by stress, strain and pore pressure as follows

$$\varepsilon_{ij} = \frac{1}{2G} \sigma_{ij} - (\frac{1}{6G} - \frac{1}{9K}) \sigma_{kk} \delta_{ij} \tag{10}$$

where G is the shear modulus of coal, μ is the Poisson's ratio of coal, δ_{ij} is the symbol of Kronecker, α is the Biot coefficient of coal, K_m is the bulk modulus of coal matrix, K is the volume modulus of coal, ε_{ij} is the component of strain tensor, and σ_{ij} is the component of stress tensor.

After the coal adsorbs gas, the adsorption expansion strain can be expressed

$$\varepsilon_s = \varepsilon_L \frac{p}{p + p_L} \tag{11}$$

where ε_L and p_L are the Langmuir strain constant and the Langmuir pressure constant, respectively.

The stress equilibrium equation can be expressed by displacement, pore pressure and adsorption expansion

$$G u_{i,jj} + \frac{G}{1 - 2\mu} u_{j,ji} - \alpha p_{,i} - K \varepsilon_{s,i} + f_i = 0 \tag{12}$$

Model establishment and numerical simulation

Model establishment

The characteristics of gas flow in coal seam are affected by excavation damage. In order to analyze the effect of damage on gas flow in coal seam, a gas extraction model is established, as shown in the Figure 1. The model is 10 meters long and 10 meters wide. There is a borehole with a radius of 1 m in the lower left corner. The normal displacement of the boundaries of model is constrained, and the symmetrical boundary condition is applied on the seepage boundary. The initial gas pressure is 3 MPa, and the gas extraction pressure is 0.1 MPa. The changes of gas pressure and gas content on the monitoring line are mainly investigated.

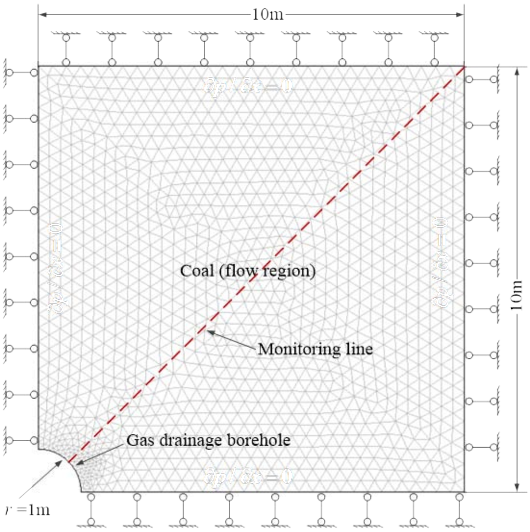


Fig. 1. Computational model geometry.

Effect of damage on gas pressure

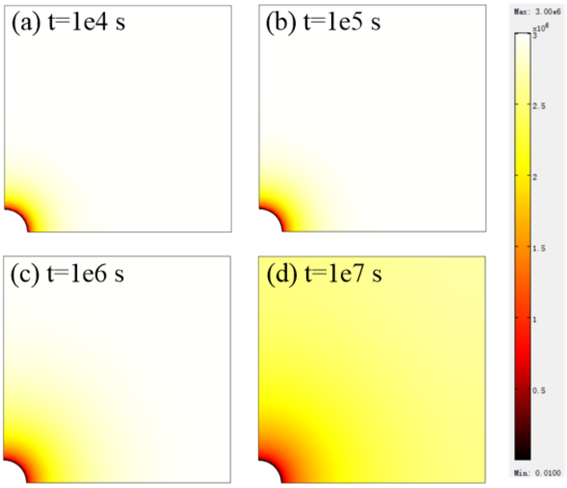


Figure 2. Gas pressure distribution in the coalbed at different times

The gas pressure of the coal seam at different times is presented in Fig. 2. The gas pressure decreases with time in the coal seam. Due to drilling, there will be excavation damage area around the drilling hole, and the coal permeability in the excavation damage area are greatly improved, which will increase the desorption and movement of gas in the coal seam, which is conducive to gas extraction. It can be seen from Fig. 2 that with the increase of extraction time, the gas pressure in coal seam decreases continuously, and the low pressure area expands continuously. Fig. 3 and Fig. 4 show the gas pressure distribution on the coal seam monitoring line at different times. It can be seen that in the initial stage, the difference of gas pressure distribution with considering damage and not considering damage is not obvious at 10^{-2} s. With the increase of initial permeability of coal seam, the gas pressure decreases. This is also due to the increase of permeability, which significantly improves the gas migration in coal seams. At the same time, the damage caused by excavation in coal seam will also increase the permeability of coal around boreholes. Although the effect of damage on gas pressure distribution is not obvious in the initial stage, the damage has a significant impact on the distribution of gas pressure in coal seam after a period of time. When considering the damage, the gas pressure decreases from 2.71 MPa to 2.52 MPa at the condition of initial permeability of 0.1×10^{-18} m^2, and the gas pressure decreases from 1.07 MPa to 0.98 MPa at the condition of initial permeability of 0.1×10^{-17} m^2.

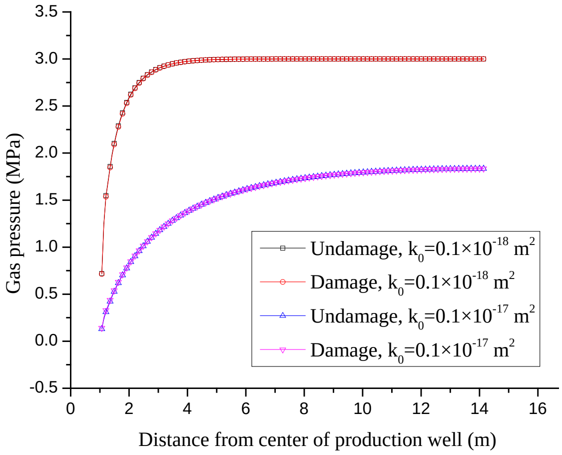


Fig. 3. Distribution of permeability ratio at $t=10^{-2}$s.

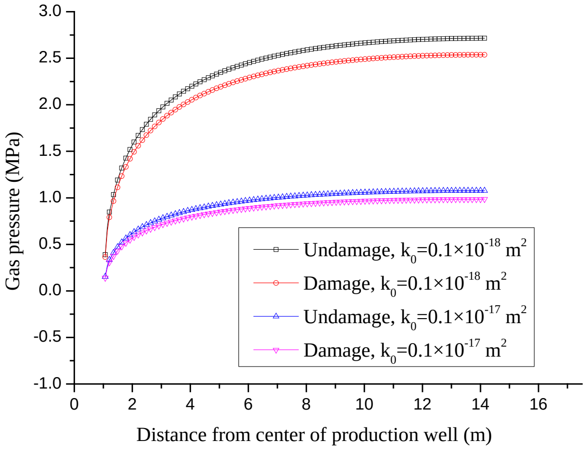
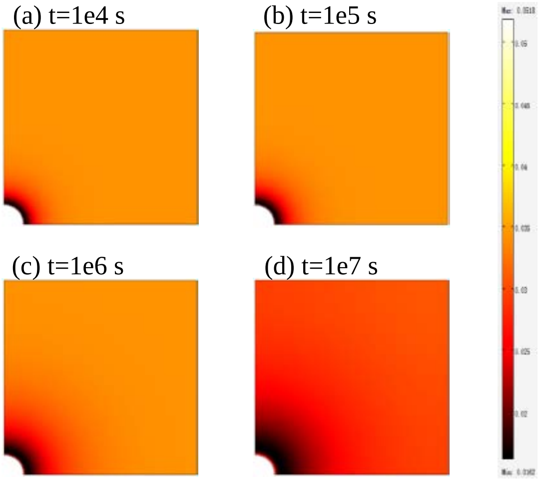


Fig. 4. Distribution of permeability ratio at $t=10^{-7}$s.

Effect of damage on gas content


(a) t=1e4 s

(b) t=1e5 s

(c) t=1e6 s

(d) t=1e7 s

Figure 5. Gas pressure distribution in the coalbed at different times

The gas content of the coal seam at different times is presented in Fig. 5. The gas content decreases with time in the coal seam. There will be excavation damage area around the borehole, which will increase the gas migration in the coal seam. The gas in the coal seam will be desorbed continuously, and the gas content will decrease continuously. It can be seen from Fig. 5 that with the increase of gas extraction time, the content of gas in coal seam decreases continuously. Fig. 6 and Fig. 7 show the gas pressure distribution on the coal seam monitoring line at different times. It can be seen that in the initial stage, the difference of gas pressure distribution between the coal seams with considering damage and not considering damage is not obvious at 10^{-2} s. With the increase of coal seam permeability, the gas adsorption content of coal seam in the stress concentration area around boreholes increases, and a peak area appears. 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 substantially. This also shows the influence of excavation damage on gas content in coal seam. Coal seam is a typical dual-porosity medium. After the formation of boreholes, under the action of pressure difference, gas in coal seam continuously flows out into boreholes. The gas pressure in coal seam drops continuously. There exists a difference between the gas pressure in coal matrix and gas pressure in fractures. The gas in the coal matrix is continuously desorbed and diffused into the fractures, resulting in the continuous decline of gas content in coal seam. Although the effect of damage on gas content distribution is not obvious in the initial stage, the damage has a significant impact on the distribution of gas content in coal seam after a period of time. When considering the damage, the gas content decreases from 0.031 m^3/kg to 0.028 m^3/kg at the condition of initial permeability of 0.1×10^{-18} m^2, and the gas content decreases from 0.024 m^3/kg to 0.023 m^3/kg at the condition of initial permeability of 0.1×10^{-17} m^2.

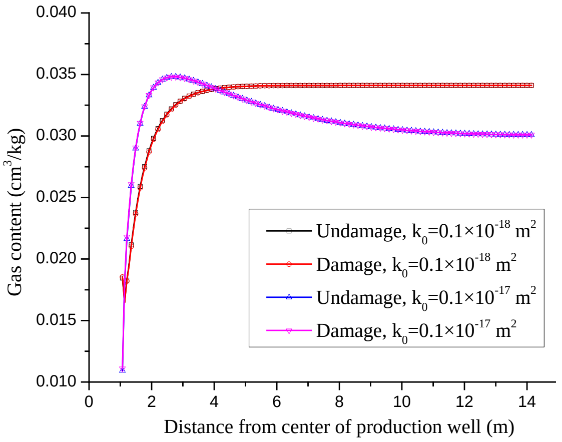


Fig. 6. Distribution of permeability ratio at different cases.

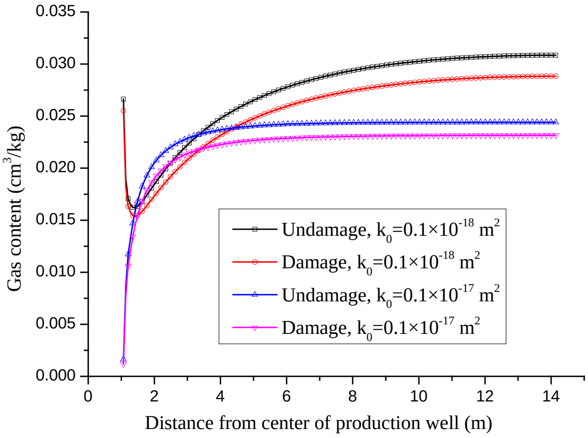


Fig. 7. Distribution of permeability ratio at different cases.

Conclusions

The damage has a significant impact on the gas extraction of coal seam. A fully coupled hydraulic-mechanical-damage model is established in this study, which takes into account the damage effect and coal-gas interaction characteristic. The numerical result shows that damage accelerates the gas flow, which is beneficial to the extraction of coal seam. Although the effect of damage on gas pressure distribution is not obvious in the initial stage, the damage has a significant impact on the distribution of gas pressure in coal seam after a period of time. When considering the damage, the gas pressure decreases from 2.71 MPa to 2.52 MPa at the condition of initial permeability of 0.1×10^{-18} m^2, and the gas pressure decreases from 1.07 MPa to 0.98 MPa at the condition of initial permeability of 0.1×10^{-17} m^2. When considering the damage, the gas content decreases from 0.031 m^3/kg to 0.028 m^3/kg at the condition of initial permeability of 0.1×10^{-18} m^2, and the gas content decreases from 0.024 m^3/kg to 0.023 m^3/kg at the condition of initial permeability of 0.1×10^{-17} m^2.

Acknowledgments

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 & Innovation Projects of Shaanxi Province (no. 2014SZS15-Z01).

Nomenclature

ρ_c - Density of coal, [kg/m^3]	ρ_g - Density of CH$_4$ at standard condition, [kg/m^3]
V_{sg} - content of absorbed gas, [-]	k_∞ - Intrinsic permeability, [m^2]
K- Bulk modulus of coal, [MPa]	K_s - Bulk modulus of coal grians, [MPa]

References

[1] Yang, X. J., *et al.*, Nonlinear dynamics for local fractional burgers' equation arising in fractal flow, *Nonlinear Dynamics*, 84 (2016), 1, pp. 3-7

[2] Xue, Y., *et al.*, The influence of the backfilling roadway driving sequence on the rockburst risk of a coal pillar based on an energy density criterion, *Sustainability*, 10 (2018), 2, pp. 2609

[3] Chang, X., *et al.*,. Mechanical performances of coal-concrete bi-material disks under diametrical compresion, *International Journal of Rock Mechanics and Mining Sciences*, 104 (2018), 3, pp. 71-77

[4] Russian, A., *et al.*, Multi-continuum approach to modelling shale gas extraction, *Transport in Porous Media*, 109 (2015), 1, pp. 109-130

[5] Orem, W., *et al.*, Organic substances in produced and formation water from unconventional natural gas extraction in coal and shale, *International Journal of Coal Geology, 126* (2014), 3, pp. 20-31

[6] Cao, Z., *et al.*, Joint Bearing Mechanism of Coal Pillar and Backfilling Body in Roadway Backfilling Mining Technology, *Computers, Materials & Continua*, 54 (2018), 2, pp. 137-159

[7] Liu, C., *et al.*, Gas emission quantity prediction and drainage technology of steeply inclined and extremely thick coal seams, *International Journal of Mining Science and Technology*, 28 (2018), 3, pp. 415-422

[8] Xue, Y., et al., An elastoplastic model for gas flow characteristics around drainage borehole considering post-peak failure and elastic compaction, *Environmental Earth Sciences*, 77 (2018), 19, pp. 669

[9] Wang, J., *et al.*, Model experiment on frost-heave force of foundation pit at deepseasonal frozen regions, *Journal of China University of Mining & Technology*, 47 (2018), 4, pp. 815-821

[10] Estrada, J. M., Bhamidimarri, R., A review of the issues and treatment options for

wastewater from shale gas extraction by hydraulic fracturing, *Fuel*, 182 (2016), 4, pp. 292-303

[11] Xue, Y., *et al.*, Evaluation of the Non-Darcy Effect of Water Inrush from Karst Collapse Columns by Means of a Nonlinear Flow Model, *Water*, 10 (2018), 9, pp. 1234

[12] Lin, B. , Shen, C., Coal permeability-improving mechanism of multilevel slotting by water jet and application in coal mine gas extraction, *Environmental Earth Sciences*,73 (2015), 10, pp. 5975-5986

[13] Liu, G., *et al.*, A fractal approach to fully-couple coal deformation and gas flow, Fuel, 240, (2019), 3, pp. 219-236

[14] Shi, S., *et al.*, Assessment of gas and dust explosion in coal mines by means of fuzzy fault tree analysis, *International Journal of Mining Science and Technology*, 28 (2018), 6, pp. 991-998

[15] Zhu, J., *et al.*, The interdependency of pore structures and coal dynamic failures. *Journal of China University of Mining & Technology*, 47 (2018), 1, pp. 97-103

Paper submitted: March 19, 2018
Paper revised: June 21, 2018
Paper accepted: August 15, 2018