Xue, Y., *et al.*: Effect of Damage on Gas Seepage Mechanism in Coal ...
THERMAL SCIENCE: Year 2019, Vol. 23, No. 3A, pp. 1323-1328

1323

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*

Introduction

Coalbed CH_4 resources are increasingly becoming an important global energy source. Coalbed CH_4 production is also important for the safety of coal mine, because coalbed methane is a harmful gas [1, 2]. Coalbed CH_4 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 CH_4 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. 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, Lin and Shen [12] numerically analyzed the coal permeability-improving mechanism of the slot crack network and the borehole gas extraction slotted by water jet underground. Liu *et al.* [13] 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. 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 σ'_{ij} is the effective stress, σ_{ij} – the total stress, α – the Biot coefficient of the coal, p – the pore pressure, and δ_{ij} – the Kronecker symbol.

The permeability of coal can be expressed:

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

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 – the compression coefficient of fracture, K – the volume modulus of coal, K_p – the volume modulus of coal fractures, and σ_e – the effective stress.

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

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

where E_0 is the elastic modulus of undamaged state and E – 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:

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

where K_0 is the initial permeability, c_f – the compression coefficient of the coal fracture, λ – the influence coefficient of damage to permeability, and σ_e – the effective stress.

The Darcy velocity of gas is expressed:

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

where μ_f is the coefficient of dynamic viscosity and k – 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 – the gas density, $\vec{q}_g$ – the Darcy velocity, Q_m – the source or sink, and t – the time variable.

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

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

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

Xue, Y., *et al.*: Effect of Damage on Gas Seepage Mechanism in Coal ...
THERMAL SCIENCE: Year 2019, Vol. 23, No. 3A, pp. 1323-1328

1325

The continuity equation of gas seepage can be obtained:

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

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:

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

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

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

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 fig. 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.
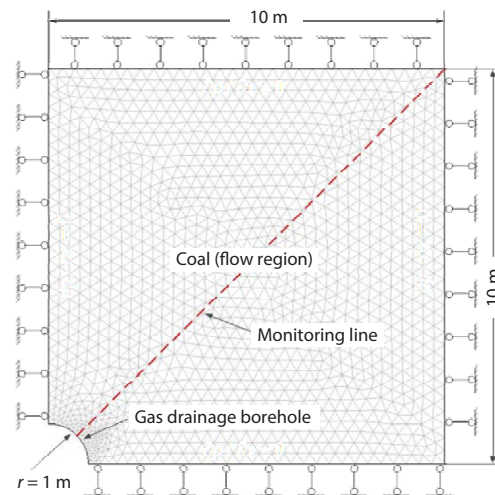

Figure 1. Computational model geometry

Effect of damage on gas pressure

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 pres-
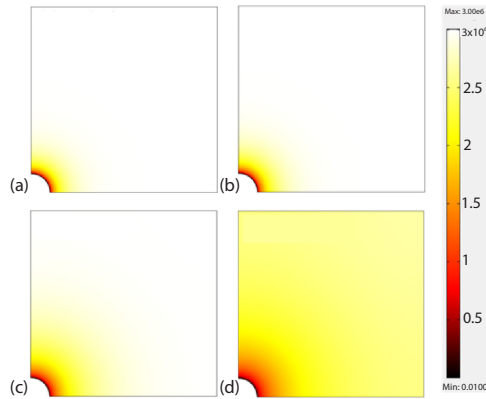
1326

Xue, Y., *et al.*: Effect of Damage on Gas Seepage Mechanism in Coal ...
THERMAL SCIENCE: Year 2019, Vol. 23, No. 3A, pp. 1323-1328

Figure 2. Gas pressure distribution in the coalbed at different time; (a) t = 1e4 s, **(b)** t =1e5 s, **(c)** t = 1e6 s, **and (d)** t = 1e7 s
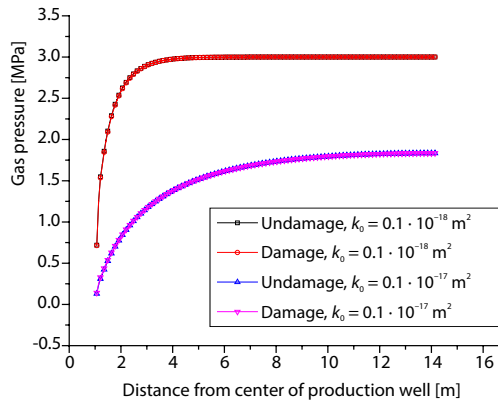

Figure 3. Distribution of permeability ratio at $t = 10^{-2}$ s

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

Figure 5. Gas pressure distribution in the coalbed at different times; (a) t = 1e4 s, **(b)** t = 1e5 s, **(c)** t = 1e6 s, **and (d)** t = 1e7 s

sure in coal seam decreases continuously, and the low pressure area expands continuously. Figures 3 and 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} second. 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 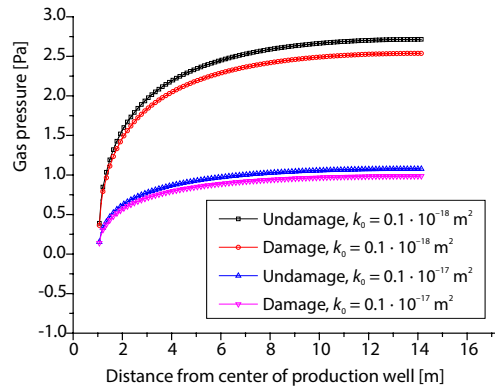is not obvious in the initial stage, the damage has a significant impact on the distribution of gas pressure in coal seam after a period of time. When considering the damage, the gas pressure decreases from 2.71 MPa to 2.52 MPa at the condition of initial permeability of $0.1 \cdot 10^{-18}$ m², and the gas pressure decreases from 1.07 MPa to 0.98 MPa at the condition of initial permeability of $0.1 \cdot 10^{-17}$ m².

Effect of damage on gas content

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
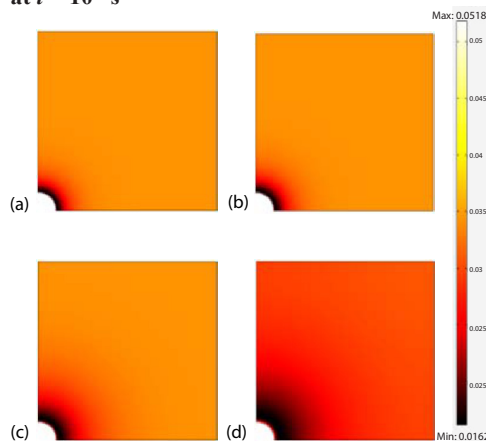
Xue, Y., *et al.*: Effect of Damage on Gas Seepage Mechanism in Coal ...
THERMAL SCIENCE: Year 2019, Vol. 23, No. 3A, pp. 1323-1328

1327

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. Figures 6 and 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} second. 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 0.031-0.028 m^3/kg at the condition of initial permeability of $0.1 \cdot 10^{-18}$ m^2, and the gas content decreases from 0.024-0.023 m^3/kg at the condition of initial permeability of $0.1 \cdot 10^{-17}$ m^2.
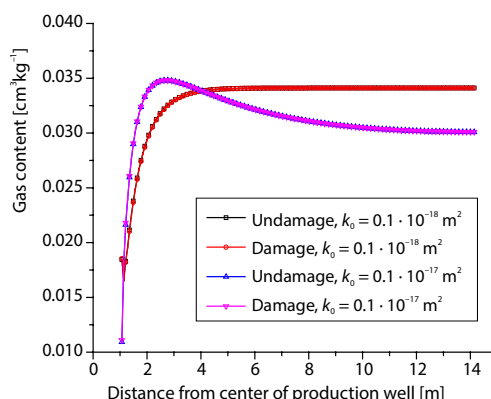
Figure 6. Distribution of permeability ratio at different cases
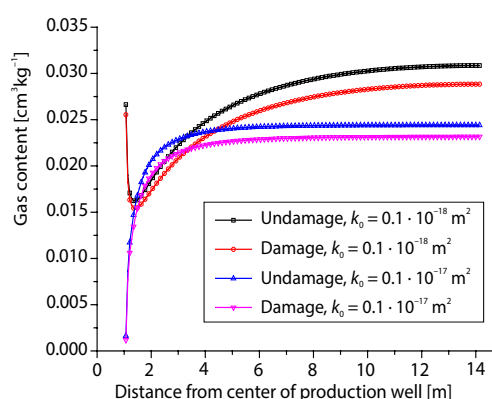
Figure 7. Distribution of permeability ratio at different cases

Conclusion

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 $0.1 \cdot 10^{-18}$ m^2, and the gas pressure decreases from 1.07-0.98 MPa at the condition of initial permeability of $0.1 \cdot 10^{-17}$ m^2. When considering the damage, the gas content decreases from 0.031-0.028 m^3/kg at the condition of initial permeability of

1328

Xue, Y., *et al.*: Effect of Damage on Gas Seepage Mechanism in Coal ...
THERMAL SCIENCE: Year 2019, Vol. 23, No. 3A, pp. 1323-1328

$0.1 \cdot 10^{-18}$ m², and the gas content decreases from 0.024-0.023 m³/kg at the condition of initial permeability of $0.1 \cdot 10^{-17}$ m².

Acknowledgment

Nomenclature

K – bulk modulus of coal, [MPa]
K_s – bulk modulus of coal grians, [MPa]
k_∞ – intrinsic permeability, [m²]
V_{sg} – content of absorbed gas, [–]

Greek symbols

ρ_c – density of coal, [kgm⁻³]
ρ_g – density of CH₄ at standard condition, [kgm⁻³]

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