Copyright © 2018 Tech Science Press CEMS, vol.115, no.3, pp.345-358, 2018

Numerical Investigation of the Effect of Sorption Time on Coal Permeability and Gas Pressure

Yi Xue[1, 2, *], Faning Dang[2], Rongjian Li[2] and Fei Liu[3]

Abstract: Adsorption deformation significantly affects the seepage characteristics of coal. However, effect of sorption time on coal permeability and gas pressure has not been investigated systematically. In this study, the sorption experiment of coal samples is conducted to elaborate the importance of sorption equilibration time. Then a coupled coal deformation and gas flow model is established considering the sorption characteristic and permeability evolution. This coupled model is implemented through finite element method to analyze the effect of sorption time on coal permeability and gas pressure. The simulation results reveal that the gas pressure of the coal will change with the adsorption time. The fracture pressure maintains a high level while the matrix pressure is relatively low during the adsorption process. The sorption time has a great influence on the distribution of gas pressure. The smaller the adsorption time is, the lower the gas pressure becomes.

Keywords: Permeability, porosity, gas pressure, adsorption time.

1 Introduction

Coal bed methane is a low-cost fuel and an unconventional source of energy, which can also pose a danger to coal production. Therefore, the pre-extraction of coal seam gas before coal seam mining can not only eliminate the risk of gas outburst, the methane also can be used as an energy source [Yu, Cheng, Jiang et al. (2004); Cao and Zhou (2015); Domingues, Baptista and Diogo (2017)]. The permeability of coal is a vital parameter in the process of coalbed methane drainage. The permeability of coal is affected by intrinsic and extrinsic factors, including effective stress, gas pressure and adsorption deformation [Cao, Du, Xu et al. (2017); Xue, Ranjith, Gao et al. (2017)]. Therefore, studying the characteristics of adsorption deformation is important for analyzing the seepage characteristics of coal [Li, Qi, Liang et al. (2010); Yin, Jiang, Hu et al. (2011); Xue, Gao and Liu (2015); Newman, Agioutantis and Leon (2017)].

Many researchers have studied the sorption characteristics of coal with different kinds of technological means. Majewska et al. [Majewska, Ceglarska-Stefańska, Majewski and Ziętek (2009)] studied the gas sorption/desorption characteristics of coal with CH_4 and CO_2 through the sorption experiments with acoustic emission system. Zhang et al. [Zhang, Ju,

[1] State Key Laboratory of Eco-hydraulics in Northwest Arid Region, Xi'an University of Technology, Xi'an 710048, China.

[2] Institute of Geotechnical Engineering, Xi'an University of Technology, Xi'an 710048, China.

[3] School of Resources and Civil Engineering, Suzhou University, Suzhou 234000, China.

[*] Corresponding Author: Yi Xue. Email: xueyi@xaut.edu.cn.

Wei et al. (2015)] measured the macromolecule structure and adsorption capacity of different kinds of metamorphic-deformed coal and suggested that internal structures determine the adsorption capacity of coal. Connell et al. [Connell, Sander, Camilleri et al. (2017)] simulated the gas drainage process by using a triple porosity model with the SIMED software and analyzed the sorption based on core flooding experiments. Peng et al. [Peng, Liu, Pan et al. (2017)] divided the matrix strain into two different parts, including internal swelling and global strain, and suggested these two swellings affected the permeability at different stage respectively. However, these studies ignore the effect of sorption time on coal permeability and it may cause a great deviation in the estimation of gas pressure.

In this study, the importance of sorption equilibration time is elaborated firstly through the sorption experiment of coal samples. Then a coupled hydro-mechanical model is established considering the sorption characteristic and permeability evolution. Finally, the effect of sorption time on coal permeability and gas pressure is studied based on this coupled model.

2 Adsorption characteristic analyses

The coal samples used in the experiment are the raw coal samples with different structural characteristics obtained from Zhao Zhuang mine at Jincheng mining area. In order to study the difference of gas adsorption capacity of coal samples, gas adsorption experiments were carried out. The adsorption experiment adopts high pressure adsorption device. First, the coal sample is placed in a vacuum drying box, and then dried and cooled to the room temperature. Then the coal sample is pumped into a coal sample tank for vacuum pumping. After the vacuum extraction is completed, the gas is filled into the coal sample tank according to the set pressure, and the experiment data are measured.

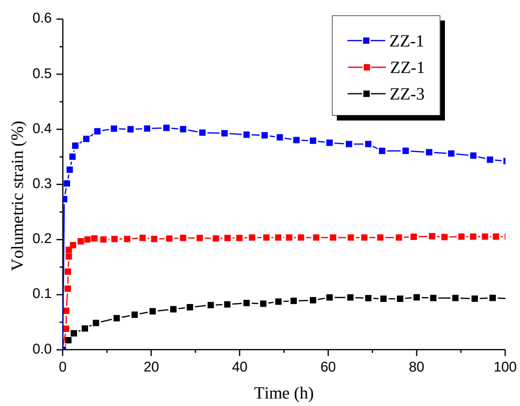

Figure 1: Sorption-induced strain against sorption time

Fig. 1 is the adsorption deformation curve of three kinds of coal samples. It can be seen from the figure that coal samples adsorbs the methane and emerges volume expansion. After a long period of time, coal deformation enters into a stable state. At the same time, it can be seen that the adsorption equilibrium time of these three coal samples is different. The coal sample ZZ-1 quickly reaches the adsorption equilibrium, while the coal sample ZZ-3 reaches equilibrium after a long time. However, the importance of adsorption equilibrium time found from the experiments did not get considerable attention. There is no effective model which can consider this characteristic of adsorption equilibrium. The coal seam is a typical dual-porosity medium reservoir which is consisted of coal matrix blocks and coal fractures. Different gas pressures exist at every point: fracture pressure p_f and matrix pressure p_m. During the adsorption process, when these two pressures reach the same value, it means the adsorption finishes. The difference between p_f and p_m will result in a long-term response to adsorption. Therefore, in the following section we investigate the sorption equilibrium characteristic based on a fully coupled hydro-mechanical (HM) model and analyze the effect of sorption equilibrium on gas pressure and coal permeability.

3 Equations of coupled model

3.1 Gas flow in fractures

The non-Darcy flow caused by inertial effect has a significant influence on gas reservoir performance and it can be expressed as [Xia, Gao, Kang et al. (2016)]

$$-\nabla p_f = \frac{\upsilon}{k_g}\vec{\mu} + \beta\rho_g\vec{\mu}\left|\vec{\mu}\right| \tag{1}$$

Where $\vec{\mu}$ is the gas velocity vector; ρ_g is the gas density; $\beta = \frac{1.75}{\sqrt{150k_g\phi^3}}$; ϕ is the porosity of coal; k_g is the permeability of coal.

The above equation can be expressed as the following form

$$\vec{\mu} = -\frac{k_g}{(1+\frac{k_g}{\upsilon}\beta\rho_g\left|\vec{\mu}\right|)\upsilon}\nabla p_f = -\frac{k_g}{f_{qi}\upsilon}\nabla p_f \tag{2}$$

Where $f_{qi} = 1 + \frac{k_g}{\upsilon}\beta\rho_g\left|\vec{\mu}\right|$ is a Forchheimer number.

For the porous media, the flow equilibrium equation can be expressed as

$$\frac{\partial}{\partial t}(\phi_f\rho_g) + \nabla(\rho_g\cdot\vec{\mu}) = Q_s(1-\phi_f) \tag{3}$$

Where ρ_g is the density of gas; $\vec{\mu}$ is the gas velocity vector; Q_s is the gas source by injection; t is the real time; this mass content m is defined as

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

Where ϕ is the porosity; ρ_{ga} is the gas density at standard conditions; ρ_c is the coal density; V_{sg} is the content of absorbed gas.

The gas absorption volume can be expressed as

$$V_{sg} = \frac{V_L p_f}{p + P_L} \tag{5}$$

Where V_L and P_L are the Langmuir volume constant and the Langmuir pressure constant.

The sorption induced volumetric shrinkage strain ε_s is assumed as

$$\varepsilon_s = \alpha_{sg} V_{sg} \tag{6}$$

Where V_{sg} is the content of absorbed gas; α_{sg} is the coefficient of sorption-induced strain.

The ideal gas law is described as

$$\rho_g = \frac{M_g}{RT} p = \frac{p}{p_a} \rho_{ga} \tag{7}$$

Where ρ_g is the gas density; M_g is the molecular weight of the gas; T is the gas temperature; R is the universal gas constant; p_a is the standard atmospheric pressure.

Then the gas flow equation can be rewritten as

$$\frac{\rho_{ga}}{p_a} \frac{\partial(\phi_f p_f)}{\partial t} + \nabla(-\frac{k_g}{\mu} \frac{\rho_g}{f_{qi}} \nabla p_f) = Q_s(1 - \phi_f) \tag{8}$$

3.2. Gas diffusion in coal matrix

The source term from the adsorption of coal matrix can be expressed as

$$Q_s = D\sigma_c (c_m - c_f) \tag{9}$$

$$\frac{\partial m_m}{\partial t} = -\frac{Mc}{\tau RT} (p_m - p_f) \tag{10}$$

where Q_s is the exchange from matrix to fractures; D is the gas diffusion coefficient; c_m is the gas concentration in matrix; c_f is the gas concentration in the fractures; σ_c is the coal matrix block shape factor.

The gas concentration in matrix and fractures can be expressed as

$$c_m = \frac{Mc}{RT} p_m \tag{11}$$

$$c_f = \frac{Mc}{RT} p_f \tag{12}$$

Where Mc is the molar mass of methane; R is the universal gas constant.

The methane exchange rate is related with the current gas content and the equilibrium gas content, therefore, the following equation is introduced to calculate the exchange rate

$$\frac{\mathrm{d}m_b}{\mathrm{d}t} = -\frac{1}{\tau}(m_b - m_e) \tag{13}$$

m_e is the equilibrium gas content under pressure p_f. The diffusion time can be expressed as

$$\tau = \frac{1}{\sigma_c D} \tag{14}$$

Where a is a shape factor; D is the diffusion coefficient, which can be expressed as Then the diffusion equation can be expressed as

$$\frac{\partial m_m}{\partial t} = -\frac{Mc}{\tau RT}(p_m - p_f) \tag{15}$$

3.3 Klinkenberg effect

The effective gas permeability k_g can be expressed as a as

$$k_g = k_\infty(1 + \frac{b}{p_f}) \tag{16}$$

Where k_∞ is the intrinsic permeability, and b is the Klinkenberg coefficient, which increases with the reduction of permeability according to Wu et al. [Wu and Pruess (1998)]

$$b = \alpha_k k_\infty^{-0.36} \tag{17}$$

Where α_k is the Klinkenberg effect coefficient, α_k =0.251.

3.4 Mechanical equilibrium equation

For the dual porosity media, the effective stress can be expressed as

$$\sigma_{eij} = \sigma_{ij} - (\beta_f p_f + \beta_m p_m)\delta_{ij} \tag{18}$$

Where σ_{eij} is the effective stress. δ_{ij} is the Kronecker delta tensor. β_f and β_m are effective stress coefficients for coal fractures and coal matrix, respectively.

The strain-displacement relation of coal is expressed as

$$\varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}) \tag{19}$$

The Navier-type equation is yielded as

$$Gu_{i,jj} + \frac{G}{1-2\mu}u_{j,ji} - \beta_f p_{f,i} - \beta_m p_{m,i} - K\varepsilon_{s,i} + f_i = 0 \tag{20}$$

3.5 Coal permeability

The general porosity model is defined as [Zhang, Liu and Elsworth (2008)]

$$\Delta\phi_f = \frac{1}{K}(\beta_f - \phi_f)(\bar{\sigma} + p_f) \tag{21}$$

Then the porosity is expressed as

$$\phi_f = \frac{1}{1+S}[(1+S_0)\phi_{f0} + \beta_f(S - S_0)] \tag{22}$$

where $S = \varepsilon_V + \frac{p_f}{K_s} - \varepsilon_s$, $S_0 = \varepsilon_{V0} + \frac{p_{f0}}{K_s} - \varepsilon_{s0}$. p_0 is the initial pressure and ϕ_0 is the initial porosity.

Besides, the permeability is correlated to the porosity according to the following exponential function

$$k_\infty = k_{\infty 0}(\phi_f / \phi_{f0})^3 \tag{23}$$

The apparent permeability in fracture system is obtained as

$$\begin{aligned} \frac{k_g}{k_{\infty 0}} &= \frac{k_\infty}{k_{\infty 0}}(1 + \frac{b}{p_f}) = (\frac{\phi}{\phi_0})^3(1 + \frac{b}{p_f}) \\ &= (1 + \frac{\alpha_k k_\infty^{-0.36}}{p_f})\{\frac{\beta_f - (\beta_f - \phi_{f0})\exp(S_0 - S)}{\phi_{f0}}\}^3 \end{aligned} \tag{24}$$

The change rate of porosity can be expressed as

$$\frac{\partial\phi_f}{\partial t} = \frac{\beta_f - \phi_f}{1+S}[\frac{\partial\varepsilon_V}{\partial t} - \frac{\partial\varepsilon_s}{\partial t} + \frac{1}{K_s}\frac{\partial p_f}{\partial t} - \frac{\beta_f - \phi_f}{1+S}\frac{\varepsilon_L p_L}{(p_f + P_L)^2}\frac{\partial p_f}{\partial t}] \tag{25}$$

4 Model establishment and analysis

4.1 Model establishment

In order to analyze the influence of adsorption on the distribution of coal permeability and gas pressure, a calculation model is established as shown in Fig. 2. The length of model is 0.1 m and width of model is 0.1 m. The upper, lower and left boundaries are restrained by normal displacement, and the right boundary is free. The zero fluxes are applied to these three boundaries, and the condition of the right boundary is the constant gas pressure 6.2 MPa. The initial pressure of the coal seam is 0.1 MPa, and the parameters in the calculation are listed in Tab. 1. A monitoring line is selected in the middle of coal mass and three monitoring points (A, B and C) are used to analyze the change law of coal permeability and gas pressure.

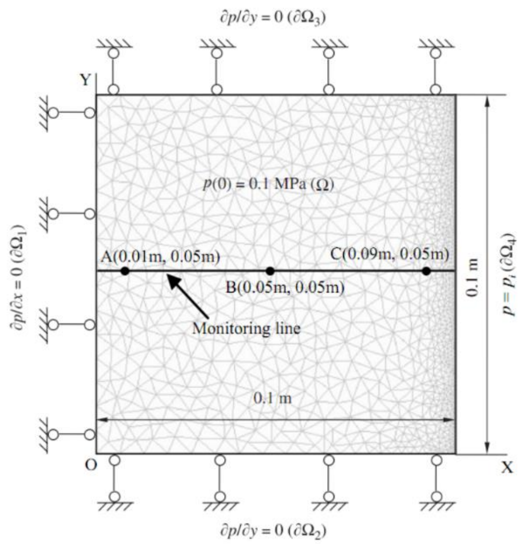

Figure 2: Geometry and boundary conditions of the calculation model

Table 1: Property parameters used in the simulation model

Parameter	Value
Young's modulus of coal (E, GPa)	2.7
Young's modulus of the coal grains, (E_s, GPa)	8.1
Density of coal, (ρ_c , kg/m^3)	1250
Poisson ratio of coal (ν , −)	0.22
Initial permeability of coal (k_0, m^2)	1×10^{-17}
Initial porosity of coal (ϕ_0 , −)	0.008
Density of methane at standard conditions (ρ_{ga} , kg/m^3)	0.717
Gas dynamic viscosity (μ , N·s/m^2)	1.84×10^{-5}
CH_4 Langmuir pressure constant (P_L, MPa)	7.2
CH_4 Langmuir volume constant (V_L, m^3/kg)	0.015
CH_4 Langmuir volumetric strain constant (ε_L , −)	0.013

4.2 Effect of adsorption deformation on gas pressure

The gas pressure of the coal will change with the adsorption time. The effective stress and adsorption deformation of coal also affect the distribution of gas pressure. Fig. 3 shows the distribution of gas pressure in coal at different times. The same color bar is used in Fig. 3. The maximum is 6.2 MPa, and the minimum is 0.1 MPa. It can be seen from the figure that the highest gas pressure appeared on the right boundary firstly. The initial pressure in the coal seam is 0.1 MPa. With the entry of the gas from the right side, the gas pressure of the coal mass increased continuously. Both p_f and p_m increase with time, and eventually reach the same pressure. There is also a difference between the matrix pressure and the fracture pressure. The pressure of coal fracture is greater than the pressure of coal matrix at 1 h, 3 h and 6 h. At the same time, with the increase of time, the difference between the matrix pressure and the fracture pressure is decreasing. Finally, the two pressures reached to 6.2 MPa at 18 h.

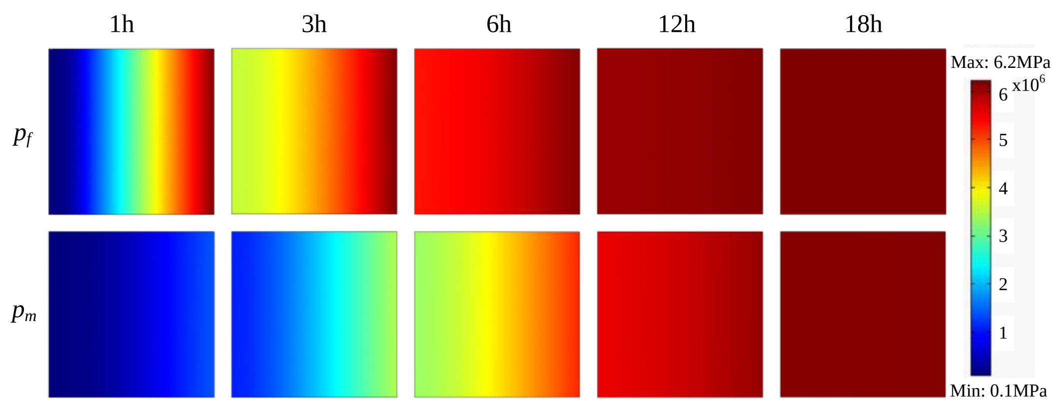

Figure 3: Gas pressure distribution at different times

The gas pressure distribution on the monitoring line is shown in Fig. 4. The gas pressure increases gradually with time. The minimum pressure of coal fracture is 3.15 MPa and 5.31 MPa corresponding to the time of 3 h and 6 h. It can be seen that the fracture pressure maintains a high level while the matrix pressure is relatively low during the adsorption process. The ratios of fracture pressure minimum and matrix pressure minimum are 100%, 371%, 167% and 100% at times 1 h, 3 h, 6 h and 18 h. Fracture pressure and matrix pressure are different in most adsorption time. However, most studies only consider the fracture pressure and neglect the matrix pressure.

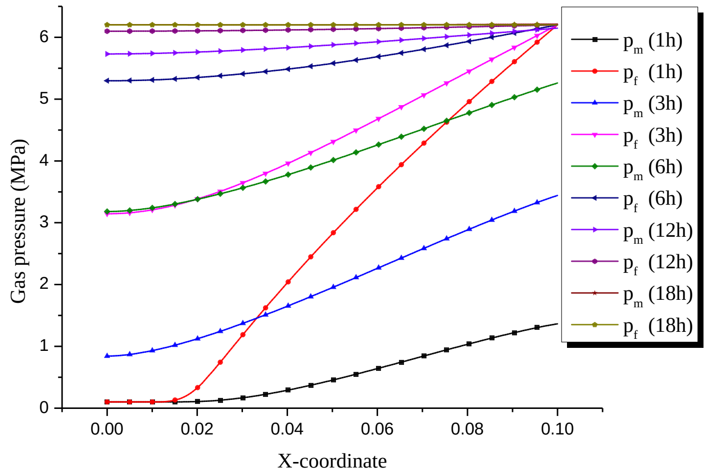

Figure 4: Gas pressure distribution along the monitoring line

4.3 Effect of adsorption deformation on permeability distribution

The permeability distribution at the monitoring line at different times is shown in Fig. 5. The permeability evolution is affected by the effective stress and the adsorption deformation. With the increase of time, the permeability of coal decreases continuously. It can be seen from the figure that the permeability of coal mass begins to decrease, and the decrease speed is fast. Finally, the decline rate changes and finally maintains a stable level. The permeability of the left side is relatively higher, while the permeability of the coal seam of the right side is relatively lower. This is because the coal of the right side is firstly adsorbed and expanded, and the fracture aperture reduces, resulting in the decrease of permeability. It shows that the influence of adsorption swelling on the right side exceeds that of the left side. Meanwhile, the influence zone of the adsorption swelling extends to the left side. Finally, more than 18 h after the gas adsorption the coal rock permeability reached a balance and remained constant.

In order to analyze the evolution characteristics of coal permeability, the permeability evolution curves of three monitoring points in the model are studied, as shown in Fig. 6. The coordinates of the three monitoring points are A (0.01 m, 0.05 m), B (0.05 m, 0.05 m) and C (0.09 m, 0.05 m). The permeability of all these monitoring points decreases with time, and finally reaches the same level. With the adsorption deformation of coal, the permeability of coal changes continuously. Finally, the adsorption deformation reaches a balanced state, and the permeability remains unchanged. The size of the permeability at three points is in order of k (A)>k (B)>k (C), and the permeability at C point finally reaches stability. The permeability evolution of different points in coal is mainly caused by gas migration and adsorption deformation of coal.

As shown in Fig. 7, the deformation of coal varies with time due to gas adsorption. When the pore pressure increases, the coal sample expands in the horizontal direction. These results show that the deformation characteristics of the calculation model are consistent with the experimental results of gas desorption. The volumetric strain caused by gas adsorption plays a vital role in the change of porosity and permeability of coal. Small variations in porosity can lead to much greater changes in permeability. The variation of permeability is affected by opposite effects of effective stress and gas desorption, and gas adsorption may decrease permeability. If the effect of gas adsorption is neglected, pore pressure of coal seam may be underestimated.

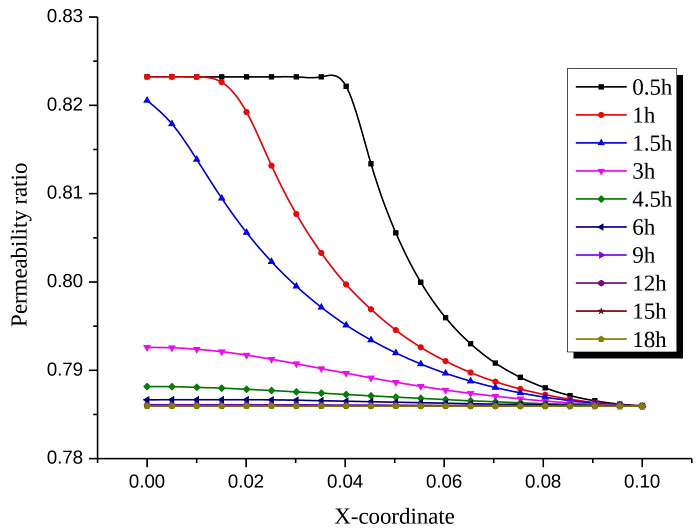

Figure 5: Permeability distribution along the monitoring line

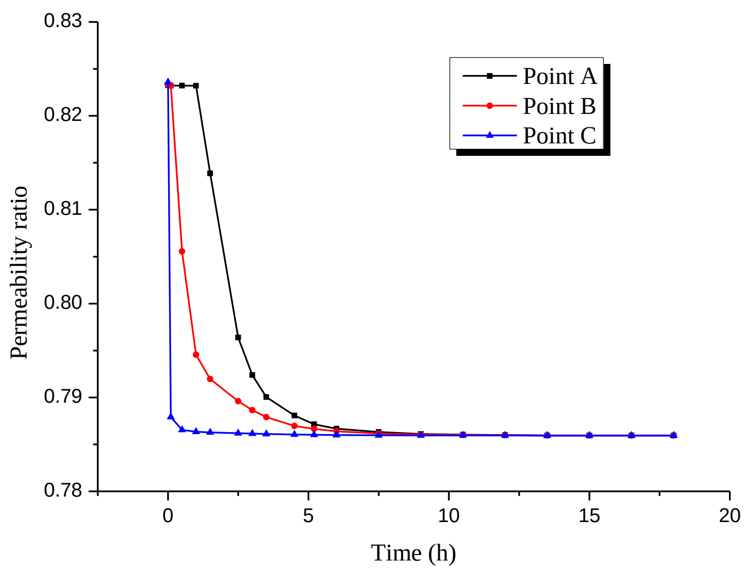

Figure 6: Permeability distribution of the monitoring points

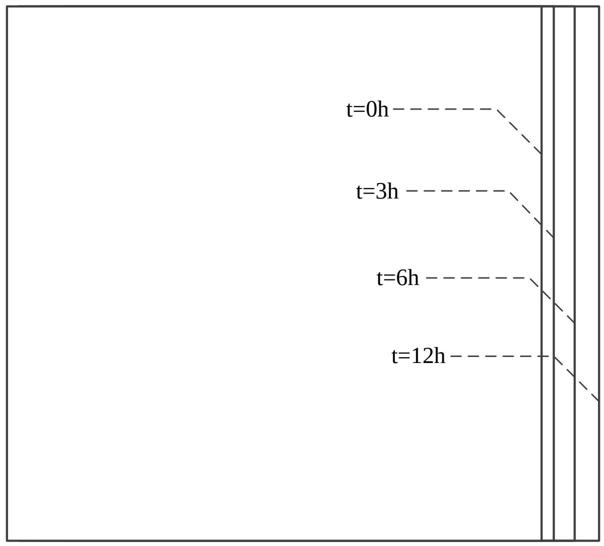

Figure 7: Evolution of the coal volume with gas desorption

4.4 Effect of adsorption time on permeability distribution

Fig. 8 shows the gas pressure distribution under different sorption time. It can be seen from the diagram, the sorption time has a great influence on the distribution of gas pressure. The smaller the adsorption time is, the lower the gas pressure becomes. The difference of the gas pressure between adsorption time 0.1 d and 1 d is greater than the difference between the adsorption time 10 d and 1 d. Fig. 9 shows the permeability distribution at different sorption times. It can be seen from the figure that the influence of sorption time on the permeability distribution is obvious, and the different sorption time also has obvious influence on the distribution of coal permeability. Similar to the gas pressure distribution, the difference of the permeability between adsorption time 0.1 d and 1 d is greater than the difference between the adsorption time 10 d and 1 d. Therefore, adsorption time is a vital factor which needs to be considered in analyzed the seepage characteristic of coal. It will affect the diffusion rate between matrix blocks band fractures. Both experiential results and simulation results indicate adsorption time significantly affect the diffusion rate and gas pressure.

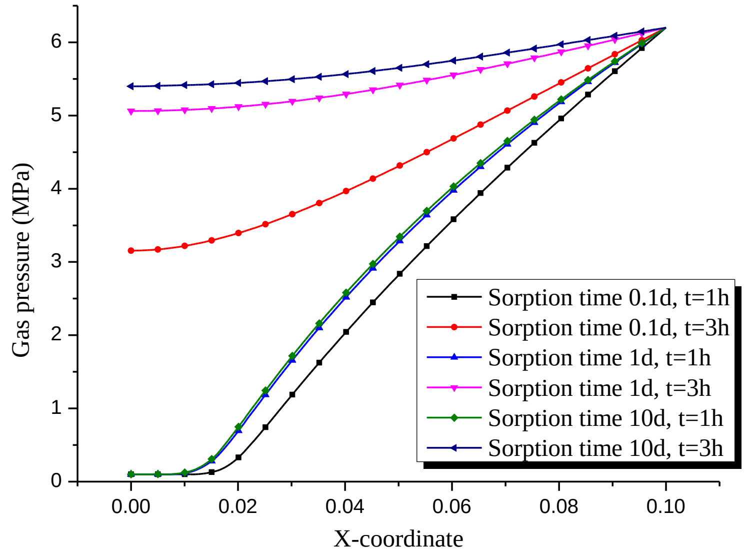

Figure 8: Gas pressure distribution with different sorption time

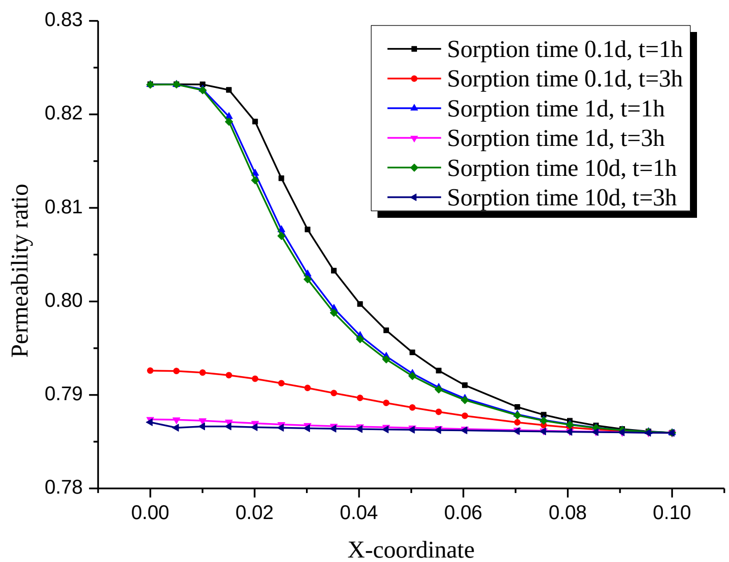

Figure 9: Permeability distribution with different sorption time

5 Conclusions

(1) The gas pressure of the coal will change with the adsorption time. Both p_f and p_m increase with time, and eventually reach the same pressure. The fracture pressure maintains a high level while the matrix pressure is relatively low during the adsorption process.

(2) With the increase of time, the permeability of coal decreases continuously. The permeability of coal mass begins to decrease, and the decrease speed is fast. Finally, the decline rate changes and finally maintains a stable level. The permeability of the left side is relatively higher, while the permeability of the coal seam of the right side is relatively lower.

(3) The sorption time has a great influence on the distribution of gas pressure. The smaller the adsorption time is, the lower the gas pressure becomes. Similar to the gas pressure distribution, the difference of the permeability between adsorption time 0.1 d and 1 d is greater than the difference between the adsorption time 10 d and 1 d.

Acknowledgments: This study is sponsored by the National Natural Science Foundation of China (No. 51679199), the Special Funds for Public Industry Research Projects of the Ministry of Water Resources (No. 201501034-04 and 201201053-03) and the Key Laboratory for Science and Technology Coordination & Innovation Projects of Shaanxi Province (No. 2014SZS15-Z01).

References

Cao, Z. Z.; Zhou, Y. J. (2015): Research on coal pillar width in roadway driving along goaf based on the stability of key block. *Computers, Materials & Continua*, vol. 48, no. 2, pp. 77-90.

Cao, Z. Z.; Du, F.; Xu, P.; Lin, H. X.; Xue, Y. et al. (2017): Control mechanism of surface subsidence and overburden movement in backfilling mining based on laminated plate theory. *Computers, Materials & Continua*, vol. 53, no. 3, pp. 187-202.

Connell, L. D.; Sander, R.; Camilleri, M.; Heryanto, D.; Pan, Z. et al. (2017): Nitrogen enhanced drainage of CO_2 rich coal seams for mining. *International Journal of Mining Science and Technology*, vol. 27, no. 5, pp. 755-761.

Domingues, M. S.; Baptista, A. L.; Diogo, M. T. (2017): Engineering complex systems applied to risk management in the mining industry. *International Journal of Mining Science and Technology*, vol. 27, no. 4, pp. 611-616.

Li, H. Y.; Qi, Q. X.; Liang, B.; Peng, Y. W.; Deng, Z. G. et al. (2010): Research on coal permeability evolution laws and multi-scale effect. *Chinese Journal of Rock Mechanics and Engineering*, vol. 29, no. 6, pp. 1192-1197.

Majewska, Z.; Ceglarska-Stefańska, G.; Majewski, S.; Ziętek, J. (2009): Binary gas sorption/desorption experiments on a bituminous coal: Simultaneous measurements on sorption kinetics, volumetric strain and acoustic emission. *International Journal of Coal Geology*, vol.77, no. 1, pp. 90-102.

Newman, C.; Agioutantis, Z.; Leon, G. B. J. (2017): Assessment of potential impacts to surface and subsurface water bodies due to longwall mining. *International Journal of Mining Science and Technology*, vol. 27, no. 1, pp. 57-64.

Peng, Y.; Liu, J.; Pan, Z.; Connell, L. D.; Chen, Z. et al. (2017): Impact of coal matrix strains on the evolution of permeability. *Fuel*, vol. 189, pp. 270-283.

Wu, Y. S.; Pruess, K. (1998): Gas flow in porous media with Klinkenberg effects.

Transport in Porous Media, vol. 32, no. 1, pp. 117-137.

Xia, T. Q.; Gao, F.; Kang, J. H.; Wang, X. X. (2016): A fully coupling coal-gas model associated with inertia and slip effects for CBM migration. *Environmental Earth Sciences*, vol. 75, no. 7, pp. 582.

Xue, Y.; Gao, F.; Liu X. G. (2015): Effect of damage evolution of coal on permeability variation and analysis of gas outburst hazard with coal mining. *Natural Hazards*, vol. 79, no. 2, pp. 999-1013.

Xue, Y.; Ranjith, P. G.; Gao, F.; Zhang, D. C.; Cheng, H. M. et al. (2017): Mechanical behaviour and permeability evolution of gas-containing coal from unloading confining pressure tests. *Journal of Natural Gas Science and Engineering*, vol. 40, pp. 336-346.

Yu, Q. X.; Cheng, Y. P.; Jiang, C. L.; Zhou, S. N. (2004): Principles and applications of exploitation of coal and pressure relief gas in thick and high-gas seams. *Journal of China University of Mining & Technology*, vol. 33, no. 2, pp. 127-131.

Yin, G. Z.; Jiang, C. B.; Hu, J.; Peng, S. J.; Li, W. P. (2011): Experimental study of thermo-fluid-solid coupling seepage of coal containing gas. *Journal of China Coal Society*, vol. 36, no. 9, pp. 1495-1500.

Zhang, W. J.; Ju, Y. W.; Wei, M. M.; Wang, G. C. (2015): Study on characteristics and mechanism of adsorption/desorption on different metamorphic-deformed coal reservoirs. *Earth Science Frontiers*, vol. 22, no. 2, pp. 232-242.

Zhang, H.; Liu, J.; Elsworth, D. (2008): How sorption-induced matrix deformation affects gas flow in coal seams: A new FE model. *International Journal of Rock Mechanics and Mining Sciences*, vol. 45, no. 8, pp. 1226-1236.