Numerical simulation of pressure gradient of coalbed gas outburst and migration considering moving boundary

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Abstract. The gas flow model is developed considering effects of gas convection, diffusion and slippage based on pore characteristics of medium and gas seepage theory in order to study the slippage effect and the effect of threshold pressure gradient on gas migration through the coal seam and determine the reasonable diameter of exposed surface. The numerical model was solved using the multiple physical coupling analysis software COMSOL Multiphysics, and good agreement was obtained by comparing the solution of numerical model with measured results. The speed of pressure change is larger when slippage effect is considered than the migration velocity of gas when slippage effect is not considered, and smaller of pressure decreases for the same cross-section. It is also concluded that the gas pressure changes faster in the coal seam, and the gas starting pressure gradient gets lower when the diameter of the exposed surface is larger. The model can be used to analyze the law of gas migration in coal seam and to determine the position of the cracking surface in coal seam effectively.

1. Introduction
Coalbed gas is the clean gas resource associated with coal instead of oil and natural gas in the 21st century. The coal bed gas brings the resource utilization to human while also causes many disasters and accidents. Coal and gas outburst is one of the main mine disasters under the combined condition of coal seam property, coal seam gas and coal seam environment. However, the mechanism of coal and gas outburst and the migration of gas in coal seam are still being studied due to the complexity of outburst mechanism of coal bed gas [1].

Li and Horne [2] studied the slippage effect of gas-liquid two-phase flow and the effect of temperature on the slippage. Miao [3] and Zhu [4] studied the seepage model of gas considering effect of slippage and pointed out that the importance of the slippage effect on gas migration according to the experiment results of gas seepage in the gas reservoir of low permeability, respectively. However, the research on the migration of coal bed gas based on coal bed methane outburst is relatively weak. It is more significant to study the influence of the slippage effect of coalbed gas for the coal seam of low permeability in China.
The coal seam belongs to the reservoir of low permeability, and it is more necessary to consider the pressure gradient of gas starting [5] in the process of gas seepage in the coal seam. The concept of start-up pressure gradient is firstly proposed in 1951. The flow occurs when the actual pressure gradient is greater than a certain critical value, which is called the start-up pressure gradient [5, 6]. It is found that the effect of depressurization is bad and the output is reduced greatly when the starting pressure gradient is considered in the simulation of the productivity of coalbed methane plaited horizontal Wells. It is very rare to consider the problem of starting pressure gradient on coal seam, and to analyze the migration law of coal bed gas under the effect of the start-up pressure gradient.

Based on the analysis above, it is very important to study the influence of slippage and start-up pressure gradient of coal bed gas in coal seam, which is directly related to the safe mining of coalbed gas. Therefore, the migration model of coalbed gas is established on the basis of the existing researches in this paper. The effects of gas slippage, threshold pressure gradient and the diameter change of exposed surface on gas migration in coal seam are studied. It provides reference for the safe exploitation of coalbed gas and the reasonable control to coal bed gas outburst.

2. Basic assumptions and governing equations
Gas flow in coal seam follows the law of conservation of mass in porous media. The coal seam is assumed to be isotropic. The equation of gas flow in the coal seam can be obtained according to the theory of porous media dynamics and gas adsorption in coal seam. Based on the mass balance equation, and the hypothesis that the adsorption gas and free gas flow out through the seepage flow, the equation can be obtained [9, 10]

\[
\frac{\partial m}{\partial t} + \nabla \cdot \left( \rho_g q_g + J_g \right) = Q_s
\]

(1)

In which, \(\rho_g\) is the gas density, kg/m\(^3\); \(q_g\) is Darcy velocity, m/s; \(t\) is the time, s; \(Q_s\) is gas source; \(m\) is the gas content, kg/m\(^3\). \(J_g\) is the diffusion velocity, kg/m\(^2\). S. When the porosity \(\phi\) is assumed to be far lower than 1, the gas content and gas density can be expressed as follows:

\[
m = \rho_g \phi + \rho_c \rho_c \frac{V_L p}{p + P_L}
\]

(2)

\[
\rho_g = \frac{M_g p}{RTZ} = \beta p
\]

(3)

In which, \(\phi\) is the porosity; \(\rho_c\) is the density of coal, kg/m\(^3\); \(\rho_g\) is gas density in the standard state; \(V_L\) is Langmuir volume, m\(^3\)/s; \(P_L\) is Langmuir pressure, MPa; \(p\) is the gas pressure, MPa; \(M_g\) is molar volume of gas, kJ·kmol\(^{-1}\); \(R\) is the molar gas constant, kJ·kmol\(^{-1}\)·K\(^{-1}\); \(Z\) is the compressibility factor, which is approximately 1 in a situation where the temperature difference is small. \(T\) is absolute temperature, K. \(\beta = M_g = M/RT\) is the coefficient of compressibility.

The effects of diffusion and seepage flow of coal bed gas follows the Fick law and Darcy's law, respectively [9, 10]
When equations (2) ~ (5) are introduced into equation (1) and varies of porosity with time is ignored, the gas flow model can be expressed as:

\[
\beta \left[ \varphi + \frac{p_0 \rho_c V_L P_l}{(p + P_l)^2} \right] \frac{\partial p}{\partial t} + \beta p \frac{\partial \varphi}{\partial t} = \nabla \left[ \beta p \frac{k}{\mu} \nabla p + D \nabla \left( \frac{p_0 \rho_c V}{P_l + p} \right) \right] \tag{6}
\]

According to Klinbenberg formular:

\[
k_g = k \left( 1 + \frac{b}{p} \right) \tag{7}
\]

In which, b is the Klinbenberg constant; If the slip effect is considered, darcy's law should be rewritten as [10]:

\[
q_g = -\frac{k}{\mu} \left( 1 + \frac{b}{p} \right) \nabla p \tag{8}
\]

After equation (8) is brought into equation (6), the gas flow model under the effect of slippage in coal seam is:

\[
\beta \left[ \varphi + \frac{p_0 \rho_c V_L P_l}{(p + P_l)^2} \right] \frac{\partial p}{\partial t} + \beta p \frac{\partial \varphi}{\partial t} = \nabla \left[ \beta p \frac{k}{\mu} \left( 1 + \frac{b}{p} \right) \nabla p + D \nabla \left( \frac{p_0 \rho_c V}{P_l + p} \right) \right] \tag{9}
\]

3. Numerical simulation model and parameters
A simple two-dimensional geometric model was developed as:

![Figure 1. Sketch model of uncovering coal device](image)

D1 and D2 are the diameter of the coal section and coal sample chamber, respectively. The ratio of D1 and D2 is 0.2 in Figure 1a and 1 in Figure 1b. L is the length of coal sample (0.5m). The parameters used in the model are shown in Table 1[12, 13].
Table 1. Parameters and values of the model

| Name of parameter | Value       |
|-------------------|-------------|
| $P_{i}$, MPa      | 0.596       |
| $V_{m}$, m$^3$/s  | 40          |
| $\rho_{s}$, kg/m$^3$ | 0.714        |
| $\rho_{c}$, kg/m$^3$ | 1450        |
| $k$, m$^2$       | 1.48e-18 (1.45e-17[11]) |
| $\mu$, Pa.s     | 1.14e-4     |
| $\rho_0$, kg/m$^3$ | 0.1          |
| $\varphi$       | 11.6        |
| $D$, m$^3$/s     | 1.2e-12     |
| $P_0$, MPa       | 1           |
| $c$, MPa         | 0.1         |
| $\sigma$, MPa    | 20          |
| $\sigma_t$, MPa  | 0.1         |

4. Results and Discussion

4.1. The influence of slippage and surface diameter on coal bed gas migration

The pressure boundary at D1 is adopted to be a constant of 0.06MPa. The remaining boundaries are zero flux boundaries. The initial value is set to be 1.2MPa. The diagram below shows the distribution of gas pressure in stable state after gas outburst considering the slip effect or not. $b=0.49$MPa when effect of slippage is considered [10]. It can be seen that gas has reached a stable state in the coal seam after the migration of 1000d from Figure 2. Gas pressure changes slowly when the effect of gas slippage is not considered. The gas pressure is changed to be 0.68 MPa at about 0.1 m in the steady state. It is at about 0.2 m as the pressure varies to be 0.68 MPa considering the effect of slippage. The capacity of gas migration in a given boundary condition is nearly twice as fast as the gas migration when the slip effect is considered. It is indicated that the effect of slippage is obvious for gas migration in the coal seam in cases of low pressure. The gas pressure decreases with time and the pressure changes more obviously with time increases.

Figure 2. The effect of slippage on gas migration in coal seam

The influence of the diameter of the exposed surface in the round coal seam on the gas migration is analyzed under the effect of gas slippage. The results are shown in Figure 3. (D1/D2=0.2). The gas pressure at 0.1m from the circular exposed surface is about 0.68MPa when the effect of gas slippage is
not considered under the same boundary condition and initial condition (as shown in Figure 2). When the diameter of the circular exposed surface was increased to D2, the pressure of coal seam gas at the distance of 0.1m was reduced to about 0.5MPa. The pressure of coal seam gas at 0.1m from the exposed surface is about 0.3 MPa when effect of gas slippage is considered (as shown in Figure 3), which is 60% of the pressure when the slippage effect is not considered. The results indicate that the pressure of coalbed gas decreases faster as the diameter of the circular exposed surface increases, and the slip effect accelerates the decrease of the gas pressure.

Figure 3. The influence of the diameter of circular exposed surface on gas migration in coal seam

4.2. Change of gas pressure gradient with moving boundary.

The instability layer thickness $l$ can be calculated by the formula [12]

$$l' = \frac{P_{ml} - P_h - \sigma_i}{l} > l_{cr}' = \frac{2(c + \sigma \tan \varphi)}{r}$$

(10)

In which, $P_{ml}$ is the gas pressure at the distance of $l$ from exposed surface. The gas pressure at the first stratification of the exposed surface is $P_h = P_{ml}e^{-\lambda t}$. The exposed surface pressure should be $P_h = P_{ml}e^{-\lambda t}$ when subsequent layers are unstable.

It can be obtained from experiment from the model as shown in Figure 1b [12], and

$$i_{cr}' = 6.6\text{MPa/m}$$

(11)

The seam will craze when the coal seam gas pressure gradient is greater than the given pressure gradient. The subsequent coal seam continues to craze as the pressure transfer, until the pressure change cannot meet the requirements of the cracking pressure gradient. Based on this idea, moving boundary is adopted on the coal seam boundary, such as boundary 4 in the model. Other boundary conditions are as above:

$$P = P_0 - 6.6 \times x$$

(12)

Gas injection pressure is 0.087MPa, and initial pressure is assumed to be a decay function:

$$P_0 = 0.087e^{-0.2t}$$

(13)
The results can be seen from Figure 4.

Figure 4. The changes of pressure of coal bed gas under the moving boundary

Taking the distance of 0.02m from the blasting surface as the research object, the variation law of the pressure gradient of coal seam with displacement is analyzed as shown in Figure 5. The calculation time is 0.5d, 6d and 12d. It can be seen from the Figure that, the coal seam between about 0.003~0.01 m meet the cracking pressure gradient conditions already if calculated cracking pressure gradient is 6.6 MPa/m. It can be concluded that coal seam between 0 ~ 0.01 m has crack. This is consistent with the experimental results (9~13mm) [12]. The setting of moving boundary can solve the problem of the location of final crack surface, so as to guide the development and exploitation of coal seam. The problem of coalbed gas pressure gradient change is very complicated, in the absence of field test. The advantages of this method will be more obvious in the form of full experimental data in the future.

Figure 5. Changes of pressure gradient of coalbed gas with displacement at different times

5. Conclusion
Based on the analysis above, the main conclusions are as follows:
(1) The pressure of coalbed gas reduced faster when effect of gas slippage is considered on the same profile, and the pressure of coalbed gas is reduced by 60% compared with the pressure without considering the slip effect.
(2) The faster the gas pressure changes in the coal seam as the diameter of the circular exposed surface gets larger, and the smaller the gas pressure gradient will be. The effect of gas slippage will accelerate the decrease of gas pressure.

(3) The effect of the diameter of the circular exposed surface on the starting pressure gradient gets smaller when the diameter of the circular exposed surface is smaller, and the simulation result is closer to the measured result.

(4) The moving boundary setting can be used to determine the approximate position of the cracking surface, which has certain practical significance for guiding the mining of coal seam.

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References
[1] Q.T. Hu, T.G. Zhang, J.Z. Lu, et al., Coal mine gas extraction and gas disaster prevention and control, Xuzhou, 2007.
[2] K. Li, R.N. Horne, An Experimental and Theoretical Study of Steam-Water Capillary Pressure. SPERE, 2001 477-482.
[3] S.D. Miao, Y. Wu, Mathematical model of non-darcy seepage flow in low permeability gas reservoir with gas slippage effect, Natural Gas Exploration and Development, 30 (2007) 45-48.
[4] W.Y. Zhu, H.Q. Song, D.B. He, et al., Low-velocity non-Darcy gas seepage model and productivity equations of low-permeability water-bearing gas reservoirs, Natural Gas Geoscience, 19(2008) 685-689.
[5] D.L. Zhang, X.H. Wang, Y. Song, Numerical simulation of pinnate horizontal multilateral well for coal-bed gas development in consideration of start-up pressure gradient, Acta Petrolei Sinica. 27 (2006) 89-92.
[6] H.Y. Guo, X.B. Su, An experimental measurement of the threshold pressure gradient of coal reservoirs and its significance, Natural Gas Industry, 30 (2010) 52-54.
[7] W.Y. Li, S.Y. Wang, Q.B. Qing, Exploration and development of coalbed gas, Xuzhou, China, 2003, pp. 203-228.
[8] L.W. Yang, M.Y. Sun, Peculiarities of China CBM Reservoirs and Their Dictation on CBM Production Technology, Natural Gas Industry, 21 (2001) 17-19.
[9] Y.Z. Wu, L. Meng, Y.D. Jiang, Study on the gas flowing model containing diffusion and seepage to determine gas drainage radius, China Mining Magazine, 24 (2015) 100-103.
[10] L. Meng, Research on coal damage characteristics and gas migration law of coal containing gas, China University of mining and technology (Beijing), 2013.
[11] M.H. Zhang, S.Y. Wu, Y. Niu, X.H. Meng, Numerical Simulation of Gas-solid Coupled Field in Gas Drainage Based on the Synchronous Migration Theory, Journal of Taiyuan University of Technology, 46 (2015) 60-63.
[12] Y. Xie, Q. Lu, Z.G. Du, Y. Wang, Z. Wang, Influence tests of gas seepage in laneway on outburst intensity, Safety in Coal Mines, 47 (2016) 21-27.
[13] J. Sobczyk, The influence of sorption processes on gas stresses leading to the coal and gas outburst in the laboratory conditions, Fuel, 90 (2011) 1018-1023.