Verification of Rapid Determination of Coal Seam Permeability Coefficient Based on COMSOL

Li Bingrui1,a*, Li Shubo2,b
1College of Energy and Mining Engineering, Shandong University of Science and Technology, Qingdao
2College of Safety and Environmental Engineering, Shandong University of Science and Technology, Qingdao
bemail:ly13012411971@163.com
*Corresponding author’s email: libingrui@sdust.edu.cn

Abstract: To verify the accuracy of the calculation method based on the indentation-pressure drop method to quickly determine the coal permeability coefficient, this paper simulated the gas pressure change curve of the borehole based on the COMSOL numerical simulation software. The pressure change curve obtained by setting different air permeability coefficients in the simulation software, combined with the rapid determination of the coal permeability coefficient calculation method to calculate the coal permeability coefficient, and the error between the simulated value and the calculated value is compared. The results show that the relative error between the simulated value and the calculated value is -23%~+45%, and the error between the calculated result and the simulated parameter is small, which verifies that the method of quickly determining the coal permeability coefficient based on the indentation-pressure drop method is correct and feasible. The simulation results show that the calculation results of the pressure curve obtained by the short-term simulation and the long-term simulation are basically the same. Therefore, the short-term measurement results can also be used to calculate the coal seam permeability coefficient. The rapid determination of the coal seam permeability coefficient is theoretically feasible.

1. Introduction
Coal seam permeability coefficient is an important indicator to measure the difficulty of gas flow in the coal seam. It is an important technical parameter for evaluating the difficulty of gas drainage and the risk of gas outburst [1], and it is also the most direct technical parameter for evaluating the effect of anti-reflection [2]. In China, high gas coal seams have poor air permeability, which determines that it is difficult to effectively extract gas with conventional methods. Theoretical research and mining practice have proved that technologies such as pressure relief and enhanced permeability, hydraulic fracturing, high-energy liquid disturbance fracturing and enhanced permeability, and pre-draining coal seam gas are effective ways to prevent gas disasters and increase the extraction rate [3]. However, after the implementation of antireflection, the permeability of coal seams has changed dramatically and the distribution is severely uneven. Using the permeability coefficient of a point to represent the permeability coefficient of a region cannot truly reflect the antireflection effect. Only "in-situ, dense and rapid" measurement can provide a correct evaluation.
The field measurement of coal seam permeability coefficient mainly includes the Marconi pressure method, Krichevsky flow method and pressure method proposed by Soviet scholars [4] and the borehole radial flow method proposed by Zhou Shining [5]. American scholars [6] put forward the compressible fluid steady-state radial flow theory and derives the calculation equation of coal seam permeability coefficient. Wang Zhaofeng, Wang Zhao et al. [7-10] used well test technology for reference and used pressure drop curve to calculate coal seam permeability coefficient.

A large amount of measured data shows that, except for a short time after sealing, the borehole pressure curve is a smooth curve that changes according to a certain rule [11]. The borehole pressure curve contains a lot of information and hidden features. If the regular changes and characteristics of the pressure curve can be found, then the air permeability coefficient can be quickly determined and theoretically calculated. For this reason, Yang and Li [12] proposed a fast measurement and calculation method of coal seam permeability coefficient based on the indentation-pressure drop method. This method has been applied to the actual field and the correctness of the method has been verified by field measurements. In this paper, the COMSOL numerical simulation software is used to further analyze the accuracy of the method for rapid determination of coal seam permeability coefficient from the perspective of numerical simulation.

2. Quick determination method and calculation method of air permeability coefficient

The current on-site measurement methods of coal seam permeability coefficient mainly include pressure method and flow method. The common feature of the pressure method and the flow method for in-situ determination of the coal seam permeability coefficient is that they both drill a through-bed borehole from the rock roadway perpendicular to the coal seam, and use part of the borehole in the coal seam as the measurement space. The difference is that the pressure method is to measure the natural change of gas pressure in the borehole over time, and the flow method is to measure the change process of the natural gas pressure in the borehole over time.

According to Darcy’s law, increasing the pressure difference between borehole and coal seam gas can speed up the gas migration speed in the coal seam and shorten the gas migration time. Therefore, it is theoretically feasible to realize the rapid determination of coal permeability coefficient by injecting gas into the measurement borehole. For this reason, a rapid coal permeability coefficient measuring instrument was developed, and the Fast measurement method of "bedding drilling + mobile measuring instrument + gas injection" was developed. This fast measuring instrument is mainly composed of two packers, gas pressure sensor, temperature sensor and guide rod. The basic principle of fast measurement is shown in Figure 1:

![Figure 1 Schematic diagram of fast measurement principle](image)

The measurement steps are as follows:

1) In the area to be measured, construct a bedding drill hole as a measurement hole for the coal seam permeability coefficient. Design and measure positions in the borehole at a certain interval, and measure sequentially from deep to shallow;

2) Insert the mobile permeability coefficient measuring instrument into the designated position at the bottom of the borehole;

3) Inject high-pressure gas into the two packers through the pressure bottle 1 to make the packers expand close to the borehole wall and form a space between the two packers, which is called the measurement space;
4) Inject gas into the measurement space at a certain pressure through the pressure bottle 2, stop the
gas injection after the pressure in the measurement space stabilizes for a certain period, and record the
change process of gas pressure in the measurement space with a data logger;

5) After the pressure in the measurement space drops to a stable state, stop data recording, and the
measurement at this point ends;

6) Shrink the packer, retract the mobile measuring instrument to the next measuring point, and
repeat the above operation process until the last measuring point is measured.

Based on the above measurement method, Yang and Li [12] deduced the calculation formula of
coal seam permeability coefficient under the condition of rapid measurement, and the characteristic
equation of coal seam permeability coefficient is:

\[
\ln \left( \frac{P_x + P_0}{P_x - P_0} \right) = \frac{4\pi\lambda L P_0}{V_t \ln\left( \frac{L + \sqrt{L^2 + 4r_b^2}}{2r_b} \right)} t + c
\]  

Taking \( \ln \left( \frac{P_x + P_0}{P_x - P_0} \right) \) as the ordinate and \( t \) as the abscissa, a linear function can be obtained. The
slope \( b \) of the function is as follows:

\[
b = \frac{4\pi\lambda L P_0}{V_t \ln\left( \frac{L + \sqrt{L^2 + 4r_b^2}}{2r_b} \right)}
\]

\[
\lambda = b V_t \frac{\ln\left( \frac{L + \sqrt{L^2 + 4r_b^2}}{2r_b} \right)}{4\pi L P_0}
\]  

Set \( \alpha = \frac{2\pi L}{2\pi L} \), simplify the formula (3) to get the calculation formula of the air
permeability coefficient:

\[
\lambda = \alpha b \frac{V_t}{2P_0 P_x}
\]  

Where: \( \lambda \) is the coal seam permeability coefficient, \( \frac{m^2}{(MPa \cdot s)} \); \( P_x \) is the gas pressure in the
standard state, MPa; \( \rho_0 \) is the gas density in the standard state, kg/m³; \( b \) is the slope of the
characteristic curve after coordinate transformation; \( L \) is the space length, m; \( r_b \) is the coal seam
drilling radius, m; \( P_t \) is the gas pressure in the columnar measurement space, MPa; \( P_0 \) is the original
coal seam gas pressure, MPa; \( V_t \) is the measurement space volume, m³.

3. Introduction to COMSOL and geometric model construction

COMSOL is a large-scale advanced numerical simulation software, which is widely used in various
scientific research and engineering calculation fields, and is suitable for simulating various physical
processes in the fields of science and engineering. Users can choose the required physical field and
define the relationship between them, or input their own partial differential equation (PDE) to define
the relationship between it and other equations or physical fields. The essence of multiphysics is
partial differential equations (PDEs), so if the physical phenomena can be described by partial
differential equations, COMSOL can be used for good calculation, simulation, and modelling.

The fast determination of coal seam permeability coefficient measurement calculation method
simplified the constraint conditions, ignored the diffusion and adsorption state of gas in the coal seam,
and only considered the gas seepage state in the coal seam. We constructed the following geometric
model, as shown in Figure 2:
Figure 2 Geometric model of gas seepage

As shown in the figure above, the outer cylinder represents the coal seam, and the inner hollow cylinder is in the middle of the coal seam, indicating the coal seam's bedding drilling. By defining the physical field of the geometric model, the gas pressure change in the bedding drilling is simulated.

The gas seepage flow in the coal seam obeys the law of conservation of mass and Darcy’s law, combined with the gas equation of state:

\[ \nabla (\rho \mathbf{v}) + \frac{\partial \rho}{\partial t} = 0 \]  \hspace{1cm} (5)

\[ \mathbf{v} = -\frac{K}{\mu_a} \nabla P \]  \hspace{1cm} (6)

\[ \rho = \frac{\rho_s P_s}{P} \]  \hspace{1cm} (7)

Where:
- \( \rho \) is the density of gas, kg/m³;
- \( \mathbf{v} \) is the velocity vector of gas flow;
- \( K \) is the gas permeability of the coal seam, m²;
- \( K = 2 \mu_a P_s \lambda \); \( \mu_a \) is the gas kinematic viscosity, MPa·d;
- \( P_s \) is the gas pressure in standard state, MPa;
- \( \rho_s \) is standard state gas density, kg/m³;
- \( P \) is coal seam gas pressure, MPa;
- \( \lambda \) is coal seam permeability coefficient, m²/(MPa²·s).

From (1) and (3), we can know that:

\[ \frac{\rho_s}{P_s} \rho \frac{\partial P}{\partial t} + \nabla (\rho \mathbf{v}) = 0 \]  \hspace{1cm} (8)

From (2), it can be inferred that:

\[ \mathbf{v} = -2\lambda P_s \nabla P \]  \hspace{1cm} (9)

And from (8) and (9):

\[ \frac{\rho_s}{P_s} \rho \frac{\partial P}{\partial t} + \nabla [\rho \cdot (-2\lambda P_s) \cdot \nabla P] = 0 \]

\[ \frac{\partial P}{\partial t} = \frac{2\lambda P_s^2}{\rho_s^2} \nabla^2 P \]  \hspace{1cm} (10)

Combining the characteristics of equation (10), the coefficient partial differential equation is selected to simulate the gas flow process in the coal seam, and the coefficients of the coefficient partial differential equation are defined as needed. The following is the original formula of the coefficient partial differential equation in the simulation software:

\[ e_a \frac{\partial^2 P}{\partial t^2} + d_a \frac{\partial P}{\partial t} + \nabla \cdot (-c \nabla P \cdot \alpha P + \gamma) + \beta \cdot \nabla P + \alpha P = f \]  \hspace{1cm} (11)

\[ \nabla = \left[ \frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z} \right] \]  \hspace{1cm} (12)

Where:
- \( \alpha \) is the absorption coefficient;
- \( f \) is the source term;
- \( c \) is the diffusion coefficient;
- \( e_a \) is the mass coefficient;
- \( d_a \) is the damping coefficient;
- \( \alpha \) is the convective flux convection coefficient;
- \( \beta \) is the convection coefficient;
- \( \gamma \) is the conserved flux source.

By comparing the original formula of the coefficient-type partial differential equation in the simulation software with equation (10), the coefficients of the coefficient-type partial differential equation in the simulation software are defined as needed, and then:

\[ \frac{\partial P}{\partial t} = c \cdot \nabla^2 P \]  \hspace{1cm} (13)
The initial conditions and boundary conditions are set as follows:

Initial conditions:  
\[ t = 0 \quad P = P_1 \]

Boundary conditions:  
\[ r \leq R_1 \quad P = P_1 \]
\[ R_1 < r \leq R_0 \quad P = P_0 \]

Where:  
- \( R_1 \) is the coal seam borehole radius, m;  
- \( R_0 \) is the coal seam radius, m;  
- \( P_1 \) is the gas pressure in the borehole, MPa, and  
- \( P_0 \) is the coal seam’s original gas pressure, MPa.

4. Simulation results and analysis

The three-dimensional model is modeled in COMSOL, and the parallel tetrahedron is used to divide the mesh (Figure 3); formula (10) is a second-order variable coefficient partial differential equation, which is solved by the coefficient type partial differential equation module to ensure its calculation. For the convergence of the results, the backward split formula is used in the transient solver and the step size used by the solver is changed to accurate. By setting different coal seam permeability coefficients in COMSOL, combined with the simulation curve to inversely calculate the coal seam permeability coefficient.

The relevant parameters of numerical simulation are shown in Table 1:

| parameters                        | numerical value |
|-----------------------------------|-----------------|
| Drilling radius/m                 | 0.08            |
| Drilling length/m                 | 1               |
| Coal seam thickness/m             | 2               |
| Coal seam radius/m                | 10              |
| Gas density under standard state/(kg/m³) | 0.716         |
| Gas pressure under standard state/MPa | 0.1           |
| Initial gas pressure of coal seam /MPa | 0.1           |
| Gas pressure after drilling pressure rise /MPa | 0.3            |
| \( \lambda_1 \)/m²/(MPa²·s)       | 0.001           |
| \( \lambda_2 \)/m²/(MPa²·s)       | 0.002           |
| \( \lambda_3 \)/m²/(MPa²·s)       | 0.003           |

This paper simulates the relationship of gas pressure in the borehole with time under different air permeability coefficients. The initial step length is set to 0, the maximum step length is 50 s, and the stop step length is 1000 s. The simulation curve is shown in Figure 4:

According to the simulation curve in Figure 4, the coal seam permeability coefficient calculation method is used to calculate the coal seam permeability coefficient by using the quick determination method. The characteristic equation of the simulated curve after coordinate transformation is completely consistent with formula (1) in form, as shown in Figure 5:
According to the slope of the gas pressure characteristic equation, combined with the calculation formula of the coal seam permeability coefficient under the conditions of rapid measurement, the coal seam permeability coefficient is calculated. The calculation results are shown in Table 2:

| Slope | Simulation value $m^2/(MPa^2\cdot s)$ | Calculated value $m^2/(MPa^2\cdot s)$ | Error  |
|-------|--------------------------------------|--------------------------------------|--------|
| 1     | 0.0033                               | 0.0011                              | +30%   |
| 2     | 0.0048                               | 0.00197                             | -1.5%  |
| 3     | 0.0057                               | 0.00231                             | -23%   |

To verify that this method can achieve rapid determination, the simulation time is shortened, the initial step length is set to 0, the maximum step length is 10 s, and the stop step length is 200 s. The simulation curve is shown in Figure 6:

According to the simulation curve in Fig. 6, the coal seam permeability coefficient is calculated in combination with the quick determination and calculation method of coal seam permeability coefficient. The characteristic curve of the simulation curve after coordinate transformation is shown in Figure 7:

![Simulation curve](image1)

![Characteristic curve](image2)

According to the slope of the gas pressure characteristic equation, combined with the calculation formula of the coal seam permeability coefficient under the conditions of rapid measurement, the coal seam permeability coefficient is calculated. The calculation results are shown in Table 3:

| Slope | Simulation value $m^2/(MPa^2\cdot s)$ | Calculated value $m^2/(MPa^2\cdot s)$ | Error  |
|-------|--------------------------------------|--------------------------------------|--------|
| 1     | 0.0036                               | 0.00145                             | +45%   |
| 2     | 0.0051                               | 0.00206                             | +3%    |
| 3     | 0.0061                               | 0.00243                             | +19%   |

By analyzing the above figures, we can know that:

1) The larger the coal seam permeability coefficient is, the faster the borehole pressure decreases. With the prolongation of the simulation time, the gas pressure in the borehole gradually tends to the original coal seam gas pressure.

2) With the increase of the simulation time, when the defined value of the coal seam permeability coefficient remains unchanged, the calculated value error of the simulation curve under this permeability coefficient is small, so the short-term gas pressure change curve can be used to calculate the coal seam permeability coefficient, which proves that the method of quickly measuring coal seam permeability coefficient is correct and feasible.

5. Conclusion

Based on the COMSOL simulation of gas pressure changes in the borehole, the pressure change simulation curve is obtained by setting different coal seam permeability coefficients in the simulation software, and the coal seam permeability coefficient is calculated based on the simulation curve. The results show that the simulation validates and analyzes the fast measurement method of coal seam permeability coefficient based on the indentation-pressure drop method. The difference between the simulated defined value of coal seam permeability coefficient and the calculated value of the
simulation curve under this permeability coefficient is small, so the fast measurement method of coal seam permeability coefficient based on the indentation-pressure drop method is correct and feasible.

Regardless of the fast determination and calculation method of coal seam permeability coefficient or numerical simulation, the coal seam's gas adsorption and gas diffusion are ignored. Langmuir theory and Fick's law can be added as the governing equation to analyze the calculation results.

Acknowledgments
National Natural Science Foundation of China (51804185); Shandong Taishan Scholars Team Advantage Discipline Support Program

References
[1] Lin B.Q., (2007) Theory and technology of mine gas drainage. China University of mining and Technology Press. Xuzhou.
[2] Tao Y.Q., Zhang C.L., (2018) Physical simulation test and effect evaluation of hydraulic punching pressure relief and permeability enhancement, Journal of Chongqing University, 41(10):69-77.
[3] Wang Y.F., He X.Q., (2014) Research progress and development trend of permeability enhancement technology in hydraulic coal seam. Journal of China Coal Society, 39(10):1945-1955.
[4] Song S.Z., Yu B.F., (1980) Gas preparation for dangerous coal seams. Coal Industry Press, Beijing.
[5] Zhou S.N., Lin B.Q., (1999) Theory of coal seam gas occurrence and flow. Coal Industry Press, Beijing.
[6] P.M. KEARL, et al., (1990) Air permeability measurements of the unsaturated Bandelier Tuff near Los Alamos New Mexico Journal of Hydrology, 117:225-240.
[7] Wang Z.F., Dong Q.X., (2015) Research status of coal seam permeability coefficient measurement method. Safety in Coal Mines, 46(06):16-19.
[8] Wang Z., (2014) Calculation method of coal seam permeability for radial gas flow in borehole, Henan University of Technology
[9] Lei W.J., Lei J.W., (2017) Calculation of coal seam permeability coefficient by borehole gas pressure recovery method, Coal Geology and Exploration, 45(06):28-33.
[10] Zhao P.H., Liu Y.W., (2010) Analysis and evaluation of coalbed methane testing methods. Well testing, 19(6):12-18.
[11] Lei J.W., (2017) Study on the method of calculating coal seam permeability coefficient based on borehole gas pressure recovery theory, Henan University of Technology.
[12] Yang M.Z., Li B.R., (2019) Calculation of permeability coefficient of coal seam under rapid measurement conditions. E3S Web of Conferences, 136.