INTRODUCTION

Permeability is not only a fundamental parameter to estimate methane permeation in coal seam, but also a crucial factor to restrict the exploitation and utilization of coalbed methane resources. Various dynamic disasters in the process of coal mining, such as coal-gas outburst and abnormal gas emission, are directly related to the permeability of coal seam. Accordingly, it will play a theoretical guiding role in preventing the disasters in the coalbed methane exploitation through investigating the gas migration in coal body.

The permeability of coalbed methane reservoirs is related to some factors such as the occurrence, porosity, in situ stress of coal seam, and the gas pressure. A number of models have been developed to research the permeability evolution process of coal seam. Among them, ARI model, P&M model, S&D model, and C&B model are wildly used. All these models indicate that effective stress and adsorption-induced swelling are two key factors affecting the permeability evolution of coal matrix, while gas pressure has an important influence on the effective stress and the matrix swelling. There is a linear relationship between the...
gas pressure and the effective stress, which submits to the law of effective stress.\textsuperscript{11-14} The relationship between the gas pressure and the adsorption-induced strain can be described by the Langmuir-like equation.\textsuperscript{15,16} The coal that adsors methane can be deformed, in which the adsorption-induced strain is approximately proportional to the gas adsorption capacity.\textsuperscript{17,18} Therefore, gas pressure has a profound impact on permeability evolution. The permeability decreases first and then increases as the gas pressure rises under constant confining stress,\textsuperscript{19} and the anisotropic permeability evolution model, Wang et al proposed in 2014, also confirmed this rule.\textsuperscript{20} Pini et al had tested the turning point of permeability rebound at about 2 MPa.\textsuperscript{21} Meng et al believed the coal matrix swelling had played a prevailing role in the permeability variation that is similar to roller coasters.\textsuperscript{22} On the other hand, under constant effective stress conditions, the permeability should significantly decrease when increasing the gas pressure.\textsuperscript{23,24} Harpalani and Chen reported that, as pore pressure decreased from 6.2 MPa to 0.7 MPa, the permeability of coal sample increased by 17 times.\textsuperscript{25} The macerals and pore-fracture systems of coal with different ranks are different, which is closely related to the change in coal strain and effective stress caused by matrix shrinkage. Li et al studied the dynamic process of adsorbed gas flow in coal of different ranks and pointed out that the permeability change rate was greatly affected by the maceral composition and initial permeability of coal.\textsuperscript{26} Meng et al believe that under a certain effective stress, the permeability of low-rank coal is higher than that of high-rank coal, and the influence of methane adsorption-induced expansion strain on the permeability of high-rank coal is greater than that of low-rank coal.\textsuperscript{27}

The models mentioned above are all established for coal seams or cylindrical coal samples,\textsuperscript{2} but the permeation behaviors of methane in coal particles are studied so little that the applicability of these models on coal particles needs further proof. In our previous work,\textsuperscript{5} we proposed a methane adsorption model on the basis of Darcy’s law and then solved by our self-developed software. Permeability coefficient was obtained through fitting simulation data with the adsorption experimental data. The calculative results show that the permeability coefficients have a close relationship with the adsorption pressures. However, this relationship failed to be explained or analyzed theoretically in the form of function in our last article. Thus, the main objective of this study was to address the evolution model of permeability of coal particle under the impact of adsorption pressure.

In this work, a permeability evolution model of coal particle was developed to investigate the permeability behavior of coal particle in adsorption process. This model should be verified by matching the model’s calculation values with our pervious inversion permeability data. Furthermore, the key factors of coal rank were quantitatively evaluated on how to influence the new evolution model.

### 2 | PERMEABILITY EVOLUTION MODEL OF COAL PARTICLE

#### 2.1 | Effect of gas pressure on porosity

Coal swelling due to adsorbing methane gas is a well-known phenomenon, and it controls the permeability by changing the porosity.\textsuperscript{28} Most permeability models utilize the empirical Langmuir-fit technique to deal with the effect of adsorption strain on porosity,\textsuperscript{29} but these empirical models do not explain the principle of adsorption strain fundamentally. Therefore, the interaction between gas and coal is the key to more accurately describe the swelling strain induced by gas adsorption.\textsuperscript{30} Wu considered that coal matrix expansion in adsorption process resulted from the decrease in surface pressure of pore in the coal.\textsuperscript{31} The attractions between the surface molecules of coal matrix and the inside molecules decrease after the coal adsorbed methane gas, which leads coal matrix to swell. Wei et al held the same opinion.\textsuperscript{32} According to this assumption, the reduction in surface pressure of coal induced by the adsorption can be expressed by the Gibbs adsorption equation as follows\textsuperscript{39}:

\[
d(\Delta \pi) = \frac{QR_m T}{V_m S} d \ln(p)
\]

where \(\Delta \pi\) is the variation of surface pressure from vacuum to the adsorbed state, N/m; \(Q\) is the gas adsorption capacity, m\(^3\)/t; \(R_m\) is the gas constant, 8.314 J/(mol·K); \(T\) is the temperature of coal, K; \(V_m\) is the molar volume of gas, L/mol; \(S\) is the specific surface area of coal, m\(^2\)/g; and \(p\) is the gas pressure, MPa.

The two sides of Equation (1) are integrated, and the following equation is obtained.

\[
\Delta \pi = \int_0^p \frac{QR_m T}{V_m S} d \ln(p)
\]

The gas adsorption of coal matrix satisfies the Langmuir equation.

\[
Q = \frac{abp}{1 + bp}
\]

where \(a\) and \(b\) are Langmuir adsorption constants, respectively, m\(^3\)/t, MPa\(^{-1}\).

Substituting Equation (3) into Equation (2), we can obtain.

\[
\Delta \pi = \int \frac{R_m T}{V_m S} \left[ \ln \left( \frac{1 + bp}{1 + bp} \right) \right] dp
\]

Coal is assumed as an isotropic continuous elastic body with the same adsorbed deformation in all directions,
which stays under a fully ideally constrained condition (i.e., the work done by the surface pressure of coal is completely converted into the elastic energy). Accordingly, Wu had proposed an adsorption swelling model of coal matrix\(^{31}\) as follows:

\[
\varepsilon_v = \frac{2\Delta \pi S \rho_v}{3K_j}
\]  

(5)

where \(\varepsilon_v\) is the adsorption-induced strain; \(\rho_v\) is the apparent density of coal, \(t/m^3\); and \(K_j\) is the elastic modulus of coal particles, MPa. At present, \(K_j\) of coal cylinder is measured through macroscopic uniaxial compression experiment, and the sample size is usually around 50 mm. There is still a big difference between the coal grains and the coal cylinder, and the sample size is usually around 50 mm. There is still a big difference between the coal grains and the coal cylinder, and the size of the coal grains is very small. Although the \(K_j\) of coal particles is real, it is still unrealistic to measure its specific value according to the current experimental technical means.

Effective stress refers to the force that causes the deformation of porous media. Its essence is that the porous media produces a certain degree of strain, resulting in the change of pore volume and porosity. Here, we focused on the adsorption-induced strain generated by effective stress to explore the expression of gas pressure and porosity. Put the Equation (4) into Equation (5) to get.

\[
\varepsilon_v = \frac{2\Delta \rho_v R_m T}{3V_m K_j} \ln (1 + bp)
\]  

(6)

Furthermore, Wu\(^{31}\) considered that 1/3 of the total swelling strain was converted into the swelling stress at the contact interface in the adsorption process, and the other 2/3 was the inward swelling strain that reduced the volume of the fracture. The inward swelling strain \((\varepsilon_p)\) can be calculated as.

\[
\varepsilon_p = \frac{4\Delta \rho_v R_m T}{9V_m K_j} \ln (1 + bp)
\]  

(7)

The inward swelling strain has much greater magnitude than bulk strain,\(^{23}\) and thus, it can be assumed that the coal-adsorbing gas only causes inward swelling strain, but no change in the bulk strain of coal. Considering the impact of adsorption-induced strain on porosity of coal, the porosity model can be expressed as:

\[
\varphi = \frac{V_p}{V_v} = \frac{V_p - \Delta V_p}{V_{p0}} = \varphi_0 - \frac{\Delta V_p}{V_{p0}} = \varphi_0 - \varepsilon_p
\]  

(8)

where \(\varphi\) is the porosity of coal, %; \(V_{p0}\) and \(V_p\) are the volume of pore fracture before and after deformation of coal, respectively, \(m^3\); \(\Delta V_p\) is the adsorption-induced swelling volume, \(m^3\); \(V_{v0}\) and \(V_v\) are the appearance volume before and after the deformation, respectively, \(m^3\); and \(\varphi_0\) is the initial porosity of coal, %.

By simultaneous Equations (7) and (8), the model of porosity affected by gas pressure can be established as

\[
\varphi = \varphi_0 - \frac{4\Delta \rho_v R_m T}{9V_m K_j} \ln (1 + bp)
\]  

(9)

### 2.2 Effect of gas pressure on permeability

Permeability is a basic parameter for evaluating the seepage characteristics of coalbed methane, which is directly related to the porosity. Current studies have focused on the effect of external factors on the permeability, such as in situ stress and pore pressure,\(^{2}\) while ignoring the influences from the internal factors. However, the proposed inward swelling of coal matrix should overcome this defect and further rationalized the coupling relationship between permeability and porosity.

Generally, the relationship between permeability and porosity can be expressed by the cubic law as\(^{6}\)

\[
k = k_0 \left(\frac{\varphi}{\varphi_0}\right)^3
\]  

(10)

where \(k\) is the permeability of coal, mD, \(mD = 10^{-15} m^2\); and \(k_0\) is the initial permeability of coal at a reference pressure, mD.

By substituting the Equation (9) into Equation (10), the following is obtained.

\[
k = k_0 \left[1 - \frac{1}{\varphi_0} \cdot \frac{4\Delta \rho_v R_m T}{9V_m K_j} \ln (1 + bp)\right]^3
\]  

(11)

Introduce a new parameter \(A\) as

\[
A = \frac{4\Delta \rho_v R_m T}{9V_m K_j \varphi_0}
\]  

(12)

In above equation, \(A\) is defined as the deformation coefficient of the inward swelling strain of coal matrix, which is dimensionless and related to the coal properties, temperature, and the saturated adsorption capacity.

Then the Equation (11) can be simplified as

\[
k = k_0 \left[1 - A \ln (1 + bp)\right]^3
\]  

(13)

The above equation is the permeability evolution model of coal particle that is affected by gas pressure and can be used to estimate the permeability’s variation in adsorption process.
3 | INVERSION METHOD OF GAS PERMEABILITY COEFFICIENTS

Coal body is a typical dual-porosity structure, which is composed of coal matrix and fracture. Guo et al. believed that the limit of particle size is the same as the size of coal matrix block, and they pointed out that although the large coal block looks complete, it can be regarded as the aggregation of the small coal matrix/particles. Thus, many researchers proposed the theory that gas flow in coal flows from coal matrix (low permeability) to fractures (high permeability). Previous studies have proposed a number of testing methods to examine the permeability of coal. Li et al. had used geophysical logging data to predict permeability of coal seams of Qinshui coalfield. Wang et al. had measured the permeability of cylindrical coal samples through steady-state seepage test. However, few involve the permeation behavior of methane in coal particles. Difficulties come from two aspects: (i) The particle sizes of coal particles are too small to measure their permeability through usual steady-state methods; (ii) pores play a leading role in controlling the permeability of small coal particles, but many models are designed for seepage in fractures. Therefore, our last article had proposed a practical inversion method investigating gas permeability of coal particles, which is an unsteady-state test method.

3.1 | Coal sample properties

In our last article about the permeability inversion, the experiments had been conducted on six coal samples including lignite, medium volatile bituminous, low volatile bituminous, and anthracite, and their basic properties are shown in Table 1.

3.2 | Quasi-constant pressure adsorption experiment

In previous work, we conducted a quasi-constant pressure isothermal adsorption experiment on the above six coal samples. The experimental apparatus is shown in Figure 1. Open the valves V1, V3, V4, and V5, close the remaining valves, and fill the sample tube and reference tube with helium to test the air tightness of the experimental device. It is important to note that this work needs to be repeated before each set of experiments is carried out. Pour 6 g of coal particles (180μm-250μm) into the sample tube and dry them for 4 h. The volume of reference tube and the free volume of sample tube were measured subsequently. After the sample tube was vacuum-pumped, the adsorption test began. The coal samples continuously adsorbed methane gas throughout the experiment at 35°C, but the sample tube was intermittently filled with methane so that the gas pressure was maintained near the set value. Take the designated adsorption pressure of 0.5 MPa as an example, when gas pressure dropped by 1%, the sample tube was then connected to the reference tube by V5 valve to make its pressure recover to 0.5 MPa. Repeatedly inflate the sample tube to reach the constant pressure value of the sample tube. The pressure data were constantly collected to aggregate gas reduction. In this way, the curve of cumulative methane adsorption under one constant pressure can be obtained. This experimental approach has also been demonstrated in our previously published work.

3.3 | Methane adsorption model of coal particle and solving

Our previous work had proposed a methane adsorption model of coal particle based on Darcy’s law as

\[
\frac{\partial}{\partial t} \left( \frac{ab\sqrt{P}}{1+b\sqrt{P}} + B\rho n \sqrt{P} \right) = \frac{\lambda}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial P}{\partial r} \right)
\]

(14)

where \( \lambda \) is the permeability coefficient of gas, m²/(MPa·s); \( P \) is the square of pressure of methane, \( P = \rho^2 \); MPa²; \( B \) is the free gas coefficient, m³/(t·MPa); \( \rho \) is the apparent density of coal, t/m³; and \( r \) is the radius of coal particle, m.

### Table 1 Basic properties of coal samples

| Coal mine        | \( M_{ad} (%) \) | \( A_{ad} (%) \) | \( V_{ad} (%) \) | \( FC_{ad} (%) \) | Coal rank | \( a \) (m³·t⁻¹) | \( b \) (MPa⁻¹) | \( \rho \) (t/m³) |
|------------------|-----------------|-----------------|-----------------|-----------------|------------|----------------|----------------|----------------|
| Wangniutan (WNT) | 6.620           | 3.070           | 41.090          | 49.220          | Lignite    | 8.210          | 0.308          | 1.303          |
| Anze (AZ)        | 0.681           | 8.881           | 24.598          | 65.841          | Bituminous | 16.556         | 0.749          | 1.491          |
| Shuiyu#10 (SY#10) | 0.726           | 12.840          | 24.744          | 61.690          | Bituminous | 15.479         | 0.829          | 1.307          |
| Shuiyu#9 (SY#9) ** | 0.735           | 14.741          | 18.658          | 65.866          | Bituminous | 15.625         | 0.779          | 1.432          |
| Baijigou (BJG)   | 1.124           | 10.922          | 12.998          | 74.956          | Bituminous | 26.178         | 1.124          | 1.440          |
| Yangquanwu (YQW) | 0.750           | 14.210          | 8.850           | 76.190          | Anthracite | 28.249         | 1.301          | 1.449          |

*a and b are Langmuir adsorption constants, respectively, m³/t, MPa⁻¹; \( \rho \) is the apparent density of coal, t/m³.

**SY#10 and SY#9 came from two different seams (#10 and #9) of Shuiyu coal mine.
The initial and boundary conditions can be expressed as below:

\[
\begin{align*}
& t = 0, \quad P = 0 \\
& r = 0, \quad \frac{\partial P}{\partial r} = 0 \\
& r = R, \quad P = p_w
\end{align*}
\]

(15)

where \( p_w \) is the methane pressure outside the coal particle, MPa.

The above adsorption model was transformed into a dimensionless equation in our previous article \(^{38}\) and then was discretized through finite difference method (FDM). Subsequently, a solution software system was independently developed to perform iterative calculations on the dimensionless FDM mathematic equation.

### 3.4 Inversion and results

In the inversion process, a methane adsorption experiment under quasi-constant pressure with specified coal particle size was conducted under a given pressure, and then, a permeability coefficient should be assumed to simulate the cumulative adsorption curve under the designated pressure. The gas permeability coefficient was finalized based on selecting assumed values for the permeability coefficients, which can allow the simulated curve with the quasi-pressure adsorption data (as shown in Figure 2). This inversion method has been successfully applied to our previous work.\(^{38}\)

As can be seen from Figure 2, for the AZ sample, the curve of \( \lambda = 0.0000049 \) is optimal to coincide with the whole measured data when the adsorption pressure was at 2.0 MPa. Therefore, the gas permeability coefficient of AZ sample was identified at 0.0000049 m\(^2\)/ (MPa \( \cdot \) s) under 2.0 MPa. Similarly, the gas permeability coefficient of SY#9 sample under 0.5 MPa was obtained at 0.0000093 m\(^2\)/ (MPa \( \cdot \) s), and that of YQW samples under 1.0 MPa was obtained at 0.000092 m\(^2\)/ (MPa \( \cdot \) s). In the same way, the inversion gas permeability coefficients of each coal particle had been obtained separately and are shown in Table 2.

### 4 MODEL VALIDATION AND DISCUSSION

#### 4.1 Calculation of permeability

Permeability \( k \) is a parameter representing the capacity of porous medium itself to transmit fluid, which is related to porosity, particle size, pore geometry in the direction of fluid permeating, and arrangement of solid skeleton particles. The \( k \) is different from the gas permeability coefficient \( \lambda \). The latter is the unit flow under the unit hydraulic gradient, representing the difficulty level of fluid passing through the pore skeleton.\(^{39}\) The conversion relationship between them will be discussed as below:

Here, gas flow in coal particle is considered to be obeyed to Darcy's law as:

\[
v = -\frac{k}{\mu} \frac{\partial P}{\partial r}
\]

(16)
FIGURE 2 Inversion results of gas permeability coefficients. (A) Ordinary coordinate; (B) logarithmic coordinate
where \( v \) is gas seepage velocity, m/s; and \( \mu \) is the dynamic viscosity, MPa-s.

Zhou had proposed a conception of specific flow rate of methane (\( q \), unit: m\(^3\)/m\(^2\)/s\(^{-1}\)); its equation is as follows:

\[
q = -\frac{\lambda \partial P}{\partial r}
\]

where \( q \) stands for the specific flow rate, m\(^3\)/m\(^2\)/s.

The transfer equation between gas permeability coefficient and permeability can be expressed as

\[
k = 2\mu p_n \lambda
\]

where \( p_n \) represents the atmospheric pressure under standard conditions, MPa.

The dynamic viscosity of methane is greatly affected by ambient temperature but is scarcely influenced by pressure. The dynamic viscosity of methane can be calculated as

\[
\mu = \mu_0 \left( \frac{T}{T_0} \right)^\frac{3}{2} \frac{T_0 + C}{T + C}
\]

where \( \mu_0 \) is the dynamic viscosity of methane under \( T_0 \) K, MPa-s; \( C \) is a constant that is related to gas species.

Here, \( \mu_0 = 1.03 \times 10^{-5} \) Pa-s, \( p_n = 0.101325 \) MPa, \( T_0 = 273.15 \) K, \( C = 162 \) K (methane), and it can be calculated that the \( \mu = 1.1423 \times 10^{-11} \) MPa-s when \( T = 308.15 \) K. According to Equation (18), combined with Table 2, the results of the permeability of coal particle under different conditions can be obtained and are shown in Table 3.

### 4.2 Results and analysis

Figure 3 shows the fitting results of the permeability of coal particle according to the permeability evolution model. The regression coefficients are shown in Table 4. We found that: (i) there is a negative correlation between permeability and adsorption pressure and (ii) the correlation coefficients of fittings are very high. In Table 4, we can find that correlation coefficients of five coal samples are more than 0.99, and the rest one reaches 0.98. Thus, the correctness of Equation (13) has been verified; that is, our permeability evolution model of coal particle is validated.

The adsorption pressure has a critical influence on the permeability variation. The larger the adsorption pressure, the smaller the permeability of coal particle. At present, there are three viewpoints in the mainstream to explain this phenomenon: (i) Coal matrix expands with the increase in adsorption pressure, resulting in narrowing of gas flow channel; (ii) the increased adsorption pressure causes more free gas to be adsorbed gas, which may block the micropores, and (iii) a potential factor for the permeability reduction in the process of pressure rising may be the weakening of the Klinkenberg effect. However, the fitting results in Figure 3 indicate that the solid skeleton swell of coal matrix may be the main factor of the permeability reduction. In the adsorption process, the coal matrix swells to make its volume increases, resulting in decreasing of the inner pore volume of coal particle; thus, increasing gas pressure leads to the flow path in coal particle narrower and narrower so that the permeability continuously decreases.

Wang used the method of gas desorption measurement and numerical simulation to determine the permeability of granular coal. He did not consider the effect of adsorption expansion in the numerical simulation of coal particle permeable flow. Our work takes into account the adsorptive expansion strain. Specifically, our permeability evolution model of coal particle

### 4.3 Inversion results

| Coal mine | \( V_{daf} (%) \) | Gas permeability coefficient (m\(^3\)/MPa\(^{-2}\)/s\(^{-1}\)) |
|-----------|------------------|----------------------------------------------------------|
|           | 0.5MPa | 1.0MPa | 2.0MPa | 4.0MPa |
| WNT       | 41.090 | 8.2 x 10^{-6} | 6.3 x 10^{-6} | 3.2 x 10^{-6} | 1.5 x 10^{-6} |
| AZ        | 24.598 | 9.9 x 10^{-6} | 7.7 x 10^{-6} | 4.9 x 10^{-6} | 2.1 x 10^{-6} |
| SY#10     | 24.744 | 9.8 x 10^{-6} | 7.5 x 10^{-6} | 4.8 x 10^{-6} | 2.6 x 10^{-6} |
| SY#9      | 18.658 | 9.3 x 10^{-6} | 6.8 x 10^{-6} | 3.7 x 10^{-6} | 2.5 x 10^{-6} |
| BJG       | 12.998 | 3.5 x 10^{-5} | 2.9 x 10^{-5} | 2.3 x 10^{-5} | 1.5 x 10^{-5} |
| YQW       | 8.850  | 1.1 x 10^{-4} | 9.2 x 10^{-5} | 7.7 x 10^{-5} | 5.4 x 10^{-5} |

### 4.4 Permeability of coal particle under different gas pressures

| Coal mine | Permeability (mD) |
|-----------|-------------------|
|           | 0.5MPa | 1.0MPa | 2.0MPa | 4.0MPa |
| WNT       | 0.0190 | 0.0146 | 0.0074 | 0.0035 |
| AZ        | 0.0229 | 0.0178 | 0.0113 | 0.0049 |
| SY#10     | 0.0227 | 0.0174 | 0.0111 | 0.0060 |
| SY#9      | 0.0215 | 0.0157 | 0.0086 | 0.0058 |
| BJG       | 0.0810 | 0.0671 | 0.0532 | 0.0347 |
| YQW       | 0.2546 | 0.2130 | 0.1782 | 0.1250 |
is developed based on the energy balance between the work done by surface pressure and the variation of elastic energy of coal matrix. This theoretical model has the ability to describe the mechanism of the swelling strain induced by gas adsorption, which is more accurate than the empirical model. This provides a predictive basis for calculating the permeability of coal particle. In addition, the evolution model involve so fewer parameters that it can be more transparent and easy to understand.

4.3 | Effect of coal rank on permeability

Coal rank is adopted as a significant index to characterize the coalification degree, and a higher coal rank represents a more superior metamorphic grade. Most countries use volatile matter content to classify the coal rank. A large number of volatile compounds can separate out due to hydrocarbon generation with the metamorphism of coal increases, so a
lower volatile matter content corresponds to a higher coal rank. Meanwhile, the aromatization and repolymerization of coal in the process of coal coalification lead to the rearrangement of coal structure, which is closely related to the permeability of coal.

Figure 4 reveals the relationship between the initial permeability of coal particle and the volatile matter content. Figure 4 shows that the volatile matter content has a negative exponential relationship with initial permeability. The initial permeability of WNT sample (Lignite) is the lowest at 0.0254 mD, while that of the YQW sample (Anthracite) is the largest, reaching 0.3176 mD, which is about 13 times as much as the lignite sample. The reasons may be as follows: (i) The surfaces of pore in lignite are mainly composed of some relatively loose space structures that contain high hydrogen and oxygen contents, long side chains but large spacing of aromatic sheets. These loose structures make the pore surfaces very bumpy, so the permeability of lignite is very small. However, the contents of hydrogen, oxygen, and the long side chains decrease as the coal rank grows so that the arrangement of aromatic sheets are more compact. Hence, the higher the coal rank, the higher the initial permeability,(ii) with regard to the low-rank coal such as lignite, its metamorphism is very weak due to the low coalification, and thus, the pores and fractures are so poorly developed that it has a relatively low permeability. As the coal rank increases, the coal will undergo a long-term thermal metamorphism that promotes the formation of pores and microfractures network, so the permeability of high-rank coal is enormously improved.

Figure 5 illustrates the relationship between the deformation coefficient and the volatile matter content. As can be seen, the deformation coefficient basically presents a linear growth as the volatile matter content increases. Contrary to the change in initial permeability over coal rank, the WNT sample, a kind of lignite, has the highest volatile matter content, and its deformation coefficient is also the largest, but the anthracite samples have the smallest deformation coefficient.

The variation of elastic modulus $K_j$ of coal sample may affect this phenomenon. According to the deformation coefficient’s definition, shown in Equation (12), the deformation coefficient is inversely proportional to the elastic modulus. Shen et al obtained the elastic modulus of six coal ranks through a number of triaxial mechanical loading experiments (Shen et al, 2000). The results showed that the higher the metamorphism of the coal, the greater the elastic modulus, among which anthracite had the largest elastic modulus and was the least prone to mechanical deformation. Pan et al also reported that the lower the coal rank, the smaller the elastic modulus. This also validates the results of Figure 5 to some extent; that is, the deformation coefficient is directly proportional to the volatile matter content. Furthermore, faced with the same adsorption pressure, a larger deformation coefficient corresponds to a lower permeability of coal particle. This further explains the permeability of low-rank coal sample is smaller.

| Coal mine | $k_0$ (mD) | A   | $R^2$ |
|-----------|------------|-----|-------|
| WNT       | 0.0254     | 0.652| 0.991 |
| AZ        | 0.0322     | 0.328| 0.998 |
| SY#10     | 0.0312     | 0.293| 0.999 |
| SY#9      | 0.0297     | 0.328| 0.979 |
| BJG       | 0.1036     | 0.176| 0.997 |
| YQW       | 0.3176     | 0.144| 0.994 |

**TABLE 4** Fitting results of simulated permeability of each coal sample
matrix deformation. This model had been verified by regression analysis of the inversion permeability of coal particle. The main conclusions are summarized as follows:

(i) A dynamic evolution model of coal permeability considering the impact of swelling strain was established. This model includes two main parameters, one is initial permeability of coal particle, and the other is deformation coefficient that reflects the variation characteristics of inward swelling strain of coal matrix. This proposed deformation coefficient was related to the properties of coal, the saturated adsorption capacity, and the temperature of coal.

(ii) The gas permeability coefficients of coal particles had been obtained in our previous work by inversion method. Here, these gas permeability coefficients were first converted into permeability, and then, the permeability of the same coal samples under different pressures was fitted according to the new permeability evolution equation. The results show that the theoretical calculations are matched well with the inversion permeability. Thus, the correctness of the evolution model has been verified. Furthermore, it also indicates that the solid skeleton swell of coal matrix is the main factor to reduce the permeability.

(iii) The effect of coal rank on the permeability evolution model has been investigated. The results indicate that, as the coal rank decreases, the initial permeability decreases exponentially, while the deformation coefficient basically grows in a linear trend. In addition, future work is needed to continue to explore the effect on permeability regarding the effective stresses that can only cause small deformations in coal particles.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support provided by the National Natural Science Foundation of China (Project No: 51874315, 52074303, 51604277) and the Fundamental Research Funds for the Central Universities (Project No: 2020YJSAQ04). We also appreciate the Editor’s efforts and anonymous reviewers who gave valuable comments and suggestions for our research.

ORCID

Wei Liu https://orcid.org/0000-0003-4855-4953
Hao Xu https://orcid.org/0000-0003-2417-5385

REFERENCES

1. Chen J. The fluid-structure interaction model and permeability prediction for pore-fissure in multi-scale in coalbed methane reservoir. Xuzhou: China University of Mining & Technology; 2016:150.
2. Pan Z, Connell LD. Modelling permeability for coal reservoirs: a review of analytical models and testing data. Int J Coal Geol. 2012:92:1-44.
3. Zhao W, Wang K, Cheng Y, Liu S, Fan L. Evolution of gas transport pattern with the variation of coal particle size: kinetic model and experiments. Powder Technol. 2020;367:336-346.
4. Wang K, Du F, Wang G. Investigation of gas pressure and temperature effects on the permeability and steady-state time of Chinese anthracite coal: an experimental study. J Nat Gas Sci Eng. 2017;40:179-188.
5. Liu P, Qin Y, Liu S, Hao Y. Non-linear gas desorption and transport behavior in coal matrix: experiments and numerical modeling. Fuel. 2018;214:1-13.
6. Palmer I, Mansoori J. How permeability depends on stress and pore pressure in coalbeds, a new model, SPE Annual Technical Conference and Exhibition, Denver, Colorado. 1996.
7. Pan Z, Connell LD. Modelling of anisotropic coal swelling and its impact on permeability behaviour for primary and enhanced coalbed methane recovery. Int J Coal Geol. 2011;85(3–4):257-267.
8. Shi JQ, Durucan S. Drawdown induced changes in permeability of coalbeds: a new interpretation of the reservoir response to primary recovery. Transport Porous Med. 2004;56(1):1-16.
9. Palmer I. Permeability changes in coal: analytical modeling. Int J Coal Geol. 2009;77(1–2):119-126.
10. Liu Q, Cheng Y, Zhou H, et al. A mathematical model of coupled gas flow and coal deformation with gas diffusion and klinkenberg effects. Rock Mech Rock Eng. 2015;48(3):1163-1180.
11. Chen Z, Liu J, Pan Z, Connell LD, Elsworth D. Influence of the effective stress coefficient and sorption-induced strain on the evolution of coal permeability: model development and analysis. Int J Greenh Gas Con. 2012;8:101-110.
12. Chen Z, Pan Z, Liu J, Connell LD, Elsworth D. Effect of the effective stress coefficient and sorption-induced strain on the evolution of coal permeability: experimental observations. Int J Greenh Gas Con. 2011;5(5):1284-1293.
13. Pan Z, Connell LD, Camilleri M. Laboratory characterisation of coal reservoir permeability for primary and enhanced coalbed methane recovery. Int J Coal Geol. 2010;82(3–4):252-261.
14. Zhao Y, Hu Y, Wei J, Yang D. The experimental approach to effective stress law of coal mass by effect of methane. Transport Porous Med. 2003;53(3):235-244.
15. Levine JR. Model study of the influence of matrix shrinkage on absolute permeability of coal bed reservoirs. Geological Society London Special Publications. 1996;109(1):197-212.0.
16. Shi J, Durucan S, Shimada S. How gas adsorption and swelling affects permeability of coal: a new modelling approach for analysing laboratory test data. Int J Coal Geol. 2014;128–129:134-142.
17. Cui X, Bustin RM, Chikatamarla L. Adsorption-induced coal swelling and stress: implications for methane production and acid gas sequestration into coal seams. J Geophys Res. 2007;112(B10).
18. Zhang J, Wang K, Zhao Y. Evaluation of gas sorption-induced internal swelling in coal. Fuel. 2015;143:165-172.
19. Liu J, Chen Z, Elsworth D, Miao X, Mao X. Evolution of coal permeability from stress-controlled to displacement-controlled swelling conditions. Fuel. 2011;90(10):2987-2997.
20. Wang K, Zang J, Wang G, Zhou A. Anisotropic permeability evolution of coal with effective stress variation and gas sorption: model development and analysis. Int J Coal Geol. 2014;130:53-65.
21. Pini R, Ottiger S, Burlini L, Storti G, Mazzotti M. Role of adsorption and swelling on the dynamics of gas injection in coal. J Geophys Res. 2009;114(B4).
22. Meng Y, Li Z. Experimental comparisons of gas adsorption, sorption induced strain, diffusivity and permeability for low and high rank coals. Fuel. 2018;234:914-923.
23. Connell LD, Lu M, Pan Z. An analytical coal permeability model for tri-axial strain and stress conditions. Int J Coal Geol. 2010;84(2):103-114.
24. Mitra A, Harpalani S, Liu S. Laboratory measurement and modeling of coal permeability with continued methane production: Part 1 – Laboratory results. *Fuel*. 2012;94:110-116.

25. Harpalani S, Chen G. Influence of gas production induced volumetric strain on permeability of coal. *Geotech Geol Eng*. 1997;15:303-325.

26. Li J, Lu S, Cai Y, Xue H, Cai J. Impact of coal ranks on dynamic gas flow: an experimental investigation. *Fuel*. 2017;194:17-26.

27. Meng Y, Liu S, Li Z. Experimental study on sorption induced strain and permeability evolutions and their implications in the anthracite coalbed methane production. *J Petrol Sci Eng*. 2018;164:515-522.

28. St. George JD, Barakat MA. The change in effective stress associated with shrinkage from gas desorption in coal. *Int J Coal Geol*. 2001;45(2):105-113.

29. Liu S, Harpalani S. A new theoretical approach to model sorption-induced coal shrinkage or swelling. *AAPG Bull*. 2013;97(7):1033-1049.

30. Pan Z, Connell LD. A theoretical model for gas adsorption-induced coal swelling. *Int J Coal Geol*. 2007;69(4):243-252.

31. Wu S. *Research of Methane-Coalbed Coupling Movement Theory and its Application*. Shenyang: Northeastern University; 2006:129.

32. Wei J, Qin H, Wang D, Yao B. Dynamic permeability model for coal containing gas. *J China Coal Soc*. 2015:1555-1561.

33. Xu H, Qin Y, Wang G, et al. Discrete element study on meso-mechanical behavior of crack propagation in coal samples with two prefabricated fissures under biaxial compression. *Powder Technol*. 2020;375:42-59.

34. Guo J, Kang T, Kang J, Zhao G, Huang Z. Effect of the lump size on methane desorption from anthracite. *J Nat Gas Sci. Eng*. 2014;20:337-346.

35. Liu J, Chen Z, Elsworth D, Qu H, Chen D. Interactions of multiple processes during CBM extraction: a critical review. *Int J Coal Geol*. 2011;87(3-4):175-189.

36. Robertson EP. Modeling permeability in coal using sorption-induced strain data. In: *SPE Annual Technical Conference and Exhibition*. Society of Petroleum Engineers.

37. Li J, Liu D, Yao Y, Cai Y, Qiu Y. Evaluation of the reservoir permeability of anthracite coals by geophysical logging data. *Int J Coal Geol*. 2011;87(2):121-127.

38. Liu W, He C, Qin Y, Liu P. Inversion of gas permeability coefficient of coal particle based on Darcy’s permeation model. *J Nat Gas Sci Eng*. 2018;50:240-249.

39. Zhou S, Lin B. *The theory of gas flow and storage in coal seams*. Beijing: China Coal Industry Publishing House; 1999:195.