Coal strain and permeability evolution in a 2D fractured model based on computerized tomography image reconstruction

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Abstract Coal heterogeneity, especially fracture distribution, affects the mechanical response and fluid seepage in the coal reservoir under complex stress conditions, which is important for exploiting coalbed methane and preventing gas outburst. The internal pores and fractures of coal samples were scanned using an X-ray industrial CT detection system in the State Key Laboratory of Coal Resources and Safe Mining of China University of Mining and Technology (Beijing). Based on CT images, 3D models of coal samples were reconstructed using MIMICS reconstruction and digital terrain model threshold segmentation. The number, size, and fractal dimension of pores and fractures were calculated basing from the vertical section of the 3D models to evaluate the heterogeneity of coal samples, and 2D numerical models of fractured coal samples were established using the Image Import module of COMSOL Multiphysics. Coal strain and permeability evolution during the reduction of gas pressure under constant confining stress were calculated in the numerical models. Results show that the distribution of pores and fractures is dominant to coal permeability. With gas pressure decreasing, the distribution of strain and gas flow rate in the coal samples is inhomogeneous, the maximum of which is observed at the fractures. Furthermore, the shrinkage and gas flow rate of the samples reduce with decreasing gas pressure, thereby alleviating the inhomogeneous distribution of coal strain and gas flow rate. As the gas pressure is decreased, the porosity of the coal samples decreases, the initial width of the fractures increases, and the ratio of current flow to initial flow decreases. When the gas pressure is changed from 2.0 MPa to 1.5 MPa, the ratio of current permeability to initial permeability of the coal samples initially decreases and then increases. Therefore, a dominant
switch of effective stress and gas desorption on the permeability and mechanical response occurs. When the gas pressure is decreased, the effect of coal matrix shrinkage due to gas desorption on the permeability of the coal samples exceeds the effect of effective stress.

1. Introduction

Coal is a complex porous medium that contains many irregular multi-scale pores and fracture structures and is affected by tectonic stress and coal-forming conditions. These complex pore and fracture structures constitute the storage sites and migration channels of coalbed methane. During coalbed methane migration and storage, methane appears as seepage in pores larger than 1 μm [1]. Fracture compressibility and strain boundary conditions are important factors in the evolution of coal permeability. The heterogeneity of coal and rock structure affects the mechanical response and failure deformation of coal and rock under complex stress conditions and controls the seepage of gas and water in the coal [2-3]. Understanding the mechanical response and gas seepage characteristics of fractured coal is important.

Pore pressure is an important factor that dominates gas migration in coal reservoir. The effect of pore pressure on coal and rock adsorption and seepage is complicated, including the generation of micro-cracks, expansion, and damage to coal and rock [4]. Cai applied the transient pulse method to measure the influence of seepage pores on core permeability by using classic geometry and thermodynamic fractal model and found that the pore size/volume distribution is a key parameter affecting the permeability of seepage pores [5]. Zhou indicated that vitrinite in coal is related to gas adsorption rate and microscopic structure [6].

Computed tomography (CT) scan is widely used to test the internal pore and fracture structures of coal and rock. Ju obtained the pore characteristics by CT scan experiments and constructed a 3D pore structure model with FLAC3D [7]. Yan estimated the macroscopic permeability of coal and rock through digital image processing and proposed new geometric vectorization and microstructure recognition methods [8]. Karacan used CT images to describe quantitatively the volume strain of coal adsorbing carbon dioxide [9]. Chen studied the relationship between gas seepage and joint fractal dimension through digital image processing [10]. By performing a tri-axial seepage experiment of coal samples, Wang characterized the anisotropic seepage features of coal containing gas, including the principal value and the azimuth of anisotropic coal permeability [11]. Han constructed a 3D digital coal model with macropores (>13.85 μm) by using a μCT225kVFCB system and Avizo image processing and presented an equivalent pore network model to show a sensitive zone in the relative permeability of the non-wetting phase in a low-permeability coal reservoir [12]. Zhang discussed the impact of supercritical ScCO2 on the pore structure of coal by using multi-scale characterization techniques, including low-temperature N2 adsorption, mercury intrusion porosimetry, and CT scan to capture the changes in pore fracture characteristics from nanometers to millimeters [13].

The present study applied CT scan images to reconstruct numerical models of fractured coal samples and investigated the coal deformation and permeability characteristics of fractured coal samples under depressurization conditions.

2. CT scan and reconstruction of fractured coal samples
2.1. CT experimental equipment and scan images

Coal samples were obtained from the No. 9 coal seam of Zhaogezhuang Coal Mine in Kailuan Mining Area (coal and gas outburst coal seam with a depth of 1084 m) and the No. 11 coal seam of Xinzhouyao Coal Mine in Datong Mining Area (medium shock tendency coal seam with depth 320 m). The gas content of Zhaogezhuang coal seam is 6.6–8.7 m³/t. Two groups of cylindrical coal samples with a 5 cm diameter and a 10 cm height were drilled from the coal samples with a side length greater than 20 cm parallel to the joint direction. Table 1 shows the component content of coal samples determined through industrial analysis. “ZGZ” and “XZY” represent the samples from Zhaogezhuang and Xinzhouyao mines, respectively.

| Sample | Fixed carbon content/% | Moisture/% | Ash/% | Volatile content/% | Clay mineral mass fractions/% |
|--------|------------------------|------------|-------|-------------------|-------------------------------|
| ZGZ    | 53.8                   | 1.2        | 14.7  | 30.3              | 8.3                           |
| XZY    | 68.8                   | 1.6        | 1.73  | 27.84             | 2.3                           |

The coal samples were scanned using the X-ray industrial CT inspection system (ACTIS300-320/225) provided by BIR (Bio-imaging research) in the State Key Laboratory of Coal Resources and Safe Mining of China University of Mining and Technology (Beijing). A total of 999 slices scanned were obtained along the height of the coal sample, and the scan resolution was approximately 10 μm. Processed by MATLAB, 8-bit depth and 5-fold grayscale images of the CT scan images are shown in Fig. 1. The gray value of the CT images reflects the material density of the coal samples. The darker the color of the image area, the lower the corresponding gray value. Figure 1 shows the presence of some joints and fractures in coal samples. The black, gray, and white parts represent fractures, coal matrix, and high-density inclusions, respectively.

![CT scan images](image)

**Figure 1.** The computerized tomography images of coal samples (Interval of slices is 10 mm)

2.2. Three-dimensional CT image reconstruction of coal samples

The CT images were reconstructed to 3D cores by using MIMICS to obtain the distribution characteristics of the internal fractures in coal (Figure 2a). The pores and fractures in the coal samples are shown in Fig. 2b by cutting along the axis of the 3D reconstructed images of the coal samples. In
the 3D reconstruction, the color of the pores and fractures is red to highlight its position. For sample ZGZ-1 in Fig. 2b, the red parts represent pores, and the gray and white parts represent coal matrix and high-density inclusions, respectively.

Figure 2. Three-dimensional reconstruction of coal samples and fractured images of sections

Taud et al. [15] regarded the change of gray value as a 3D terrain model (Digital Terrain Model, DTM for short). In the DTM method on threshold segmentation, the gray value \( x \) and the porosity \( \phi(x) \) satisfy

\[
\phi(x) = \frac{\sum_{r_m} (x - r_i)H(r_i)}{\sum_{r_m} xH(r_i)}
\]

where \( r_i \) is the gray value of each pixel, \( r_{min} \) is the minimum gray value in the image, \( r_{max} \) is the maximum gray value in the image, \( r_i \in [r_{min}, r_{max}] \), and \( H(r_i) \) is the range of \([r_{min}, r_{max}]\) gray histogram. \( H(r_i) \) is expressed as

\[
H(r_i) = \frac{n_i}{n}
\]

where \( n_i \) is the number of grayscale values \( r_i \) in the grayscale image, and \( n \) is the total number of image pixels.

The digital ground model of grayscale values \( r_i \) in the grayscale image is shown in Fig. 3a. In accordance with the DTM method, the gray value corresponding to the minimum value of the porosity distribution function is the threshold. Furthermore, binarized images (Fig. 3b) of the longitudinal section of the coal samples were obtained using the DTM method.
The pore and fracture structure parameters of the coal samples were calculated using ImageJ. As shown in Table 2, the coal samples differ in porosity, the maximum and average width of coal fractures, the number of pores, and the pore fractal dimensions. The pore number, porosity, and fractal dimension of ZGZ-1 and XZY-1 are greater than those of ZGZ-2 and XZY-2, respectively.

Table 2. Pore parameters of coal samples

| Sample | Porosity/% | Maximum aperture/μm | Average aperture/μm | Number of pores | Fractal dimension |
|--------|------------|----------------------|---------------------|-----------------|------------------|
| ZGZ-1  | 4.24       | 4729.06              | 123.92              | 796             | 1.23             |
| ZGZ-2  | 8.49       | 5654.55              | 186.31              | 1130            | 1.53             |
| XZY-1  | 7.75       | 6242.64              | 134.69              | 2372            | 1.54             |
| XZY-2  | 4.79       | 5148.60              | 127.69              | 668             | 1.24             |

3. Distribution of coal strain and gas flow

3.1. Numerical model of coal samples

Longitudinal sections of the coal samples (Fig. 2b) were imported into the Image Import module of COMSOL Multiphysics, and a 2D numerical model of the samples with pores and fractures was established (Figure 4). On the basis of the experimental conditions of coal sample permeability under
depressurization conditions [16-18], we suppose that the uniform stress $\sigma_c$ on the four boundaries of the model is 10 MPa and that gas flow is absent at the left and right boundaries. The initial condition of the coal samples is that the gas pressure at the top boundary is 2.0 MPa, and the gas pressure on the bottom boundary is maintained at 0.1 MPa. No vertical displacement occurs on coal bottom. The stress and displacement boundary conditions of ZGZ-1 are shown in Fig. 4. The numerical model has 950 cells and 517 nodes.

![Numerical model and boundary conditions of ZGZ-1](image)

**Figure 4.** Numerical model and boundary conditions of ZGZ-1

3.2. Governing equations of the numerical model

Basing from previous porous elastic mechanical models of coal and rock [16-18], we assume that the stress–strain relationship of the coal samples is

$$\Delta\sigma_{ij} = 2G\Delta\varepsilon_{ij} + \lambda\Delta\varepsilon_{ij}\delta_{ij} + (\lambda + \frac{2}{3}G)\Delta\varepsilon_{ij}\delta_{ij}$$

(3)

where $\sigma_{ij}$ is the stress tensor, $\varepsilon_{ij}$ is the strain tensor, $\delta_{ij}$ is the Kronecker symbol, $G$ is the shear modulus, $\lambda$ is the Lamé constant, $\varepsilon_v$ is the volume strain, and $\varepsilon_s$ is the gas adsorption strain. The volume strain of the coal samples due to gas adsorption follows the Langmuir equation:

$$\varepsilon_s = \frac{\varepsilon_p p}{p + p_L}$$

(4)

where $\varepsilon_p$ is the Langmuir maximum adsorption strain, $p$ is the average gas pressure, and $p_L$ is the gas pressure corresponding to 50% of the maximum adsorption strain. Coal permeability is influenced by the effective stress and gas adsorption [17]:

$$k = k_0 \exp \left\{ -3C_f \left( p_0 - p \right) \left[ 1 - \frac{K\varepsilon_p p_L}{(p + p_L)(p_0 + p_L)} \right] \right\}$$

(5)

where $k_0$ is the initial permeability, $C_f$ is the fracture volume compressibility coefficient, and $K$ is the bulk modulus. The gas flow rate and permeability have the following relationship:

$$v = -\frac{k}{\mu} \nabla p$$

(6)
where \( v \) is the gas flow rate, \( \mu \) is the dynamic viscosity of the fluid, and \( \nabla p \) is the pressure gradient. Equations (3)–(6) are the governing equations of the numerical model for coal deformation and permeability. Given that the main component of coal seam gas is methane gas (CH₄) and based on relevant experimental results [18], the parameters used in the numerical model are listed in Table 3.

### Table 3. Parameters of the coal numerical model

| Parameter                                      | ZGZ-1 | ZGZ-2 | XZY-1 | XZY-2 |
|------------------------------------------------|-------|-------|-------|-------|
| Elastic modulus \( E/\text{MPa} \)            | 900   | 1289  | 750   | 880   |
| Poisson ratio \( \nu \)                       | 0.34  | 0.35  | 0.36  | 0.38  |
| Fracture volume compressibility factor \( C_f/\text{MPa}^{-1} \) | 0.66  | 0.66  | 0.13  | 0.13  |
| Langmuir maximum adsorption strain \( \varepsilon_p/10^{-3} \) | 3.92  | 2.35  | 2.92  | 2.86  |
| Gas pressure corresponding to 50% maximum adsorption strain \( p_L/\text{MPa} \) | 0.78  | 0.78  | 1.29  | 1.30  |

### 3.3 Numerical simulation results

#### 3.3.1 Coal strain distribution

The distribution of the \( x \)-axial and \( y \)-axial strains in the coal interior is not uniform, as shown in Figure 5. Coal samples shrink in the \( x \)-axial and \( y \)-axial directions, but some expansion strains occur in the pore and fracture area. For example, the maximum \( x \)-axial and \( y \)-axial shrinkage strain values of ZGZ-1 are \( 4.80 \times 10^{-3} \) and \( 6.86 \times 10^{-3} \), respectively. However, an expansion occurs on the fractures, causing the values in the \( x \)-axial and \( y \)-axial direction to reach \( 4.79 \times 10^{-3} \) and \( 5.44 \times 10^{-3} \), respectively.
### Figure 5. Distribution of coal sample strains

3.3.2 Gas flow distribution

Similar to the strain distribution, the gas flow distribution in coal is also non-uniform. The gas flow distributions of the coal samples are shown in Figure 6. The distribution of gas flow rate in the coal matrix is relatively uniform, but the gas flow rate increases suddenly at the pores and fractures. The average flow velocities of the four coal samples are $1.05 \times 10^{-3}$, $7.1 \times 10^{-4}$, $1.24 \times 10^{-3}$, and $8.9 \times 10^{-4}$ m/s. The maximum gas flow rate appears in the fractures, and that of ZGZ-1 can reach $6.80 \times 10^{-1}$ m/s. The maximum gas flow rates of ZGZ-1, ZGZ-2, XZY-1, and XZY-2 are 212.4, 145.6, 27.1, and 23.0 times greater than those of coal bottom, respectively.

### Figure 6. Gas flow distribution of coal samples

4. Analysis and discussion
4.1 Influence of fractures on gas flow

Shrinkage strains appear in the coal sample matrix while expansion strains on the fractures. Taking ZGZ-1 as an example, when the inlet gas pressure changes from 2.0 MPa to 1.0 MPa, the x-axial strains on the reference line of the coal sample are as shown in Figure 7, the reference line is 20 mm away from the bottom, and the x-axial strains of the coal sample rise suddenly at the position of the fracture. The total shrinkage and the expansion in the fractures reduce with decreasing inlet pressure. The gas flow distribution of the coal sample also has the same trend. As shown in Fig. 7, the highest gas flow rate of ZGZ-1 at the reference line occurs in the fracture. As the inlet pressure decreases from 2.0 MPa to 1.0 MPa, the maximum gas flow rate of ZGZ-1 reduces 0.54 times.

![Figure 7. Coal strains and gas flow distribution under different gas pressures](image)

4.2 Influence of gas pressures on coal permeability

Compared with the experimental data, the numerical results of coal permeability ratio $k/k_0$ according to Equation (5) can be obtained. As shown in Fig. 8, $k/k_0$ initially decreases and then increases with decreasing gas pressure. With ZGZ-1 as an example, when the initial inlet pressure is 2.0 MPa, the initial permeability ratio $k/k_0$ is 1, which decreases to 0.98. When the gas pressure is reduced to 1.5 MPa, $k/k_0$ gradually rises. When the inlet pressure is 0.3 MPa, $k/k_0$ reaches 2.73. The relative errors between numerical and experimental data are 0.9%–4.2%. For Xinzhouyao samples, the numerical results of permeability ratio are close to the experimental data, and the relative errors are 1.1%–11.5%. The above-mentioned results of coal strains, gas flow, and permeability are consistent with previous experimental data. When gas pressure decreases, coal permeability of coal change from decreasing to increasing at a certain gas pressure which was defined as rebound gas pressure by Shi and Durucan [19]. The numerical
results suggest that the rebound gas pressures of the coal samples are between 1.5 MPa and 2.0 MPa, which is consistent with experimental measurements [17, 19-21].

Figure 8. Permeability ratio $k/k_0$ of coal samples

Four types of outlet depressurization schemes (within 10 h) were designed to investigate the gas flow rate evolution of coal samples with fractures. As shown in Figure 9, $t$ represents the pressurization time.

Figure 9. Cumulative flow correlation curve for depressurization conditions

The total gas flow quantity during outlet gas pressure reduction within 10 h is shown in Fig. 10. The schemes corresponding to gas flow from high to low are from Scheme 1 to Scheme 4. The higher the gas pressure difference, the more gas flow rate. The gas flow is related to the pore and fracture diameters of the coal samples. The cumulative gas flow of XZY-1 is lower than that of the other samples, and the cumulative gas flow of XZY-2 is the highest among samples. No fractures appear in XZY-1, but two fractures are visible in XZY-2 (Fig. 2b). Thus, the fractures in the coal samples have critical effects on gas flow.
5. Conclusion
A numerical model of coal samples containing pores and fractures is presented to embody the distribution characteristics of pores and fractures in coal. The distribution characteristics of internal strains and gas flow in the coal samples under depressurization conditions are investigated in this work. The main conclusions are as follows:

(1) The distribution characteristic of pores and fractures is presented by combining CT scan, MIMICS 3D reconstruction, and DTM threshold segmentation. The fractal dimensions of coal vertical section are used to evaluate the heterogeneity of the coal samples from the medium shock tendency and gas outburst coal seams.

(2) The distribution of pores and fractures primarily causes the inhomogeneous distribution of coal strains and gas flow. Coal samples generally shrink, but expansion strains appear in the pore and fracture area. Gas flow suddenly rises and falls nearby the pores and fractures in coal. The maximum gas flow rate in the pores and fractures can reach 23.0–212.4 times more than the outlet gas flow rate.

(3) During depressurization, the numerical results indicate that coal permeability initially decreases and then increases with decreasing gas pressure. The inlet pressure corresponding to the permeability rebound is between 1.5 and 2.0 MPa. The gas pressure difference between the inlet and outlet has a critical effect on coal permeability. The higher the gas pressure difference, the more gas flow rate. This result is consistent with the experimental observation.

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