Classification of Pore–fracture Combination Types in Tectonic Coal Based on Mercury Intrusion Porosimetry and Nuclear Magnetic Resonance

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ABSTRACT: Differences in content, distribution, and connectivity of pores and fractures with different sizes in coal lead to different modes of gas migration. An accurate classification of pore–fracture combination types in coal can lay a foundation for studying gas migration. High-pressure mercury intrusion and nuclear magnetic resonance (NMR) experiments were conducted on coal samples collected from the Changping coal mine in Jincheng City, Shanxi Province, and Pingdingshan no. 4 mine in Pingdingshan City, Henan Province, China. The fractal dimensions of pores with different sizes were calculated using the Menger model. By combining the data with T2 spectra obtained by NMR, critical values for distinguishing diffusion pores from seepage pores–microfractures were determined. In addition, the main parameters affecting development of diffusion pores and seepage pores–microfractures and pore–fracture connectivity were analyzed, and a comprehensive evaluation index system for pores and fractures was established by selecting eight indices. Based on the method combining the analytical hierarchy process with multiparameter superposition, a method for determining critical values, establishing the evaluation index system, and classifying pore–fracture combination types was formed. The pore–fracture combination types in the test coal samples were classified according to the experimental data. The results indicate that the critical values for distinguishing diffusion pores from seepage pores–microfractures based on fractal dimensions obtained through mercury intrusion porosimetry and T2 spectra obtained by NMR are 72 nm and 2.5 ms, respectively. The studied coal samples can be classified into three combination types, separately characterized by high diffusivity and permeability and poor pore–fracture connectivity; low diffusivity, high permeability, and good pore–fracture connectivity; and low diffusivity and permeability and good pore–fracture connectivity. In the coal samples from the Changping coal mine, diffusion pores and seepage pores–microfractures are developed, while the connectivity between pores and fractures is poor. The coal samples from Pingdingshan no. 4 mine have undeveloped diffusion pores and seepage pores–microfractures but good connectivity between pores and fractures. The research results provide a method for classifying pore–fracture combination types in coal samples taken from different regions.

1. INTRODUCTION

Coal is a multiscale pore–fracture medium. The content, distribution, and connectivity of pores and fractures with different sizes are different, which leads to different modes of gas migration. Accurately classifying pore–fracture combination types in coal can lay a foundation for studying gas migration. Scholars have characterized pore–fracture structures with different sizes by using various methods, such as high-pressure mercury intrusion porosimetry (MIP), low-temperature liquid nitrogen adsorption, nuclear magnetic resonance (NMR), and scanning electron microscopy (SEM). For high-pressure MIP, by analyzing types of mercury injection and ejection curves and combining the data with fractal theory,1 critical values for distinguishing diffusion from seepage pores are separately determined and connectivity between pores and fractures measuring more than 7.2 nm is
evaluated.\textsuperscript{2−5} The liquid nitrogen adsorption method describes and characterizes the distribution of pores with a size of 2−100 nm and adsorption characteristics of pores to nitrogen by analyzing morphologies of hysteresis loops on adsorption and desorption curves and calculating fractal dimensions.\textsuperscript{6−9} As for the NMR method, by measuring \( ^1H \) signals of fluid in rock and coal and plotting \( T_2 \) spectra, the types of pore structures in coal were classified. It is generally considered that three spectral peaks with relaxation times at 0.5−2.5, 20−50 ms, and greater than 100 ms separately represent micropores, mesopores, and macropores and microfractures.\textsuperscript{10−13} The SEM observation method can be used to directly observe the morphologies of nano-/micropores on the surfaces of coal samples\textsuperscript{14,15} but cannot characterize the three-dimensional (3-D) structure of coal.

To overcome the deficiency of the single test method in the pore size measurement range and characterization, some researchers have modified and superimposed the test results obtained by various methods and jointly characterized the pores with different sizes in coal.\textsuperscript{16−19} They thereby focus on the characterization of pores and fractures with different sizes but rarely classify the combinations thereof. By collecting the coal samples from the Changping coal mine in Shanxi province and Pingdingshan no. 4 mine in Henan province, high-pressure MIP and NMR experiments were conducted and an evaluation index system established for differentiation pores and seepage pores−microfractures. Moreover, a three-step method for classifying the pore−fracture combination types in coal was proposed, thus providing a method for classifying the pore−fracture combination types in coal in different regions.

2. RESEARCH METHODS

There are diffusion pores and seepage pores−microfractures in coal, and gas migrates in pores and fractures with different sizes in different modes. Gas in diffusion pores mainly migrates by diffusion, while gas in seepage pores−microfractures mainly migrates by non-Darcy flow with a starting pressure gradient or Darcy flow.\textsuperscript{20,21} To classify pore−fracture combination types, we first conducted NMR and high-pressure MIP tests on the same coal sample. The critical values for distinguishing diffusion pores from seepage pores−microfractures were determined based on \( T_2 \) spectra yielded by NMR and fractal dimensions obtained by MIP. Furthermore, the valuation index system for pores and fractures with different sizes was built and the pore−fracture combination types were classified.

2.1. Determination Methods for Critical Values for Diffusion Pores and Seepage Pores−Microfractures.

2.1.1. NMR-based Determination Method for the Critical Value for Distinguishing Diffusion Pores from Seepage Pores−Microfractures. The coal samples were saturated for 12 h with water and then tested by NMR to obtain \( T_2 \) spectral curves under different pore sizes in coal. The morphologies of \( T_2 \) spectral curves reflect the distribution of pores and fractures with different sizes. The smaller the \( T_2 \) value, the smaller the corresponding pore size. The area enclosed by peak values represents the proportion of pores of such a size, and the width of each peak indicates the quality of sorting of such pores and fractures. Moreover, the number of peaks denotes the degree of connectivity between pores and fractures of different sizes.

Theoretically, there should be three peaks in a \( T_2 \) spectrum obtained by NMR on the coal samples, separately corresponding to diffusion pores, seepage pores, and microfractures.\textsuperscript{11} Based on \( T_2 \) values, the critical value for distinguishing diffusion pores from seepage pores−microfractures could be determined.

2.1.2. MIP-based Determination Method for the Critical Value for Diffusion Pores and Seepage Pores−Microfractures. The critical values for distinguishing diffusion pores from seepage pores−microfractures in the coal samples can be classified by differences in the fractal dimensions of pores of different sizes. When testing pores with the MIP, the relationship between pore size and pressure satisfies the Washburn equation,\textsuperscript{22} namely

\[
p(r) = -2\delta \cos \theta / r
\]

where, \( p(r) \) and \( r \) indicate the applied pressure (MPa) and pore radius (nm) of coal, respectively; \( \delta \) represents the surface tension of mercury (480 dyne/cm); \( \theta \) denotes the contact angle between mercury and the solid surface (140°).

By substituting these parameters into Formula 1, the following formula can be obtained

\[
p(r) \propto r = 7.5 \times 10^3
\]

Differentiating both sides of Formula 2, the following formula can be obtained

\[
p(r)dr + rdp(r) = 0
\]

That is

\[
dr = -[r/p(r)]dp(r)
\]

In the experiment, the total pore volume under a given pressure is equal to the mercury volume injected into the pore, namely

\[
dV = dV_p(r)
\]

where, \( V \) and \( V_p(r) \) represents the total pore volume under a given pressure (cm\(^3\)/g) and the mercury volume injected into the pore (cm\(^3\)/g), respectively.

The idea of Menger sponge can be used to characterize the pore structure of coal,\textsuperscript{23} namely

\[
dV/dr \propto r^{2-D}
\]

By simultaneous use of Formulae 2, 4−6, the following formula can be obtained

\[
dV_p(r)/dp(r) \propto r^{4-D}
\]

By taking logarithms on both sides of Formula 7, the following formula can be obtained

\[
\log[dV_p(r)/dp(r)] \propto (4 - D) \log r \propto (D - 4) \log p(r)
\]

where, \( D \) represents the fractal dimension of pores in the coal samples. By plotting \( \log[dV_p(r)/dp(r)] \) and \( \log P(r) \), the slope \( K \) can be obtained, giving the fractal dimension as follows

\[
D = 4 + k
\]

By using this method, the relationship between \( \log[dV_p(r)/dp(r)] \) and \( \log P(r) \) can be deduced. This indicates that the pore structure in the coal samples changes abruptly at a certain inflection point. The research demonstrates that the mode of gas migration also changes.\textsuperscript{4} The pore radius corresponding to the inflection point of the two line segments is taken as the critical value for distinguishing diffusion pores from seepage pores−microfractures in coal.
2.2. Establishment of the Evaluation Index System.

The difficulty of gas migration and production is jointly determined by development degrees and connectivity of diffusion pores and seepage pores—microfractures. The main parameters affecting the development of diffusion pores and seepage pores—microfractures and pore—fracture connectivity were analyzed, and we established the associated evaluation index system.

2.2.1. Selection of Parameters for Evaluating the Degree of Development of Diffusion Pores and Seepage Pores—Microfractures. After determining the critical values for distinguishing diffusion pores from seepage pores, the porous volumes of diffusion pores and seepage pores—microfractures can be separately obtained while performing MIP tests on coal samples. The larger the volume of diffusion pores (or seepage pores—microfractures), the more numerous the corresponding pores in the coal samples, indicating that diffusion pores (or seepage pores—microfractures) in the coal samples are more developed. Therefore, the porous volume becomes an important parameter with which the degree of development of diffusion pores can be evaluated (or seepage pores—microfractures). The mercury ejection efficiency can be calculated based on mercury injection and ejection curves in the MIP test. The lower the mercury ejection efficiency is, the wider the hysteresis loop between the mercury injection and ejection curves and the more numerous the open pores; otherwise, there are more semiclosed pores. The fractal dimension reflects the complexity of pore size distribution. The smaller the fractal dimension, the simpler the pore size distribution.

When measuring T2 spectra of the coal samples by NMR, after determining the critical relaxation time of diffusion pores and seepage pores—microfractures, their percentages of porous volumes can be determined according to the morphology of the T2 spectra. Moreover, the relative amounts of diffusion pores and seepage pores—microfractures can be characterized, thus revealing the degree of development of diffusion pores (or seepage pores—microfractures).

2.2.2. Selection of Parameters for Evaluating Connectivity between Pores and Fractures. According to distribution of pores and fractures with different sizes, the uniformity of pore—fracture distribution in the coal samples can be evaluated. When other conditions are the same, the more uniform the pore—fracture distribution, the higher the connectivity. A characteristic structural coefficient is the reciprocal of the product of the coefficient of variation of pores and fractures and structural coefficient, and the smaller its value, the better the pore—fracture structure and connectivity in the coal samples. Mercury saturation is the ratio of the maximum amount of mercury injected in the coal samples per unit mass to the total porosity. The larger the value, the more the connected pores. The more continuous the spectral peaks in morphologies of T2 spectra obtained by NMR, the better the connectivity of diffusion pores, seepage pores, and fractures in the coal samples. Therefore, the distribution uniformity, characteristic structural coefficient, mercury saturation, and morphology of T2 spectra can be regarded as important parameters for evaluating connectivity between pores and fractures.

In accordance with the above parameters, the parameters including porous volume, percentage of porous volume, mercury ejection efficiency, and fractal dimension of pores were selected to evaluate the degree of development of diffusion pores and seepage pores—microfractures. Parameters, such as pore—fracture distribution uniformity, characteristic structural coefficient, mercury saturation, and the type of T2 spectra were selected for comprehensive evaluation of the connectivity between pores and fractures. Thus, a comprehensive evaluation index system for diffusion pores and
seepage pores—microfractures was established, as shown in Figure 1.

2.3. Classification Method for the Pore—Fracture Combination Types. After establishing the evaluation index system, based on the high-pressure MIP and NMR test results, thresholds of the parameters were determined by combining with other research results and using the analytical hierarchy process. Different thresholds were scored and the pore—fracture combination types were finally evaluated. The classification method for the pore—fracture combination types is shown in Figure 2.

3. RESULTS AND DISCUSSION

3.1. Determination of the Critical Values for Distinguishing Diffusion Pores from Seepage Pores—Microfractures. 3.1.1. Classification of Diffusion Pores and Seepage Pores—Microfractures Based on NMR. Based on the NMR test data, T2 spectra of the coal samples were plotted. By combining the spectra with the correspondence between peaks and pore—fracture systems in different positions, diffusion pores and seepage pores—microfractures were classified (Figure 3).

As shown in Figure 3, T2 spectra of different coal samples are different, but the positions of peaks on each spectrum are similar. The T2 spectrum corresponding to diffusion pores is generally in the range of 0.05—2.5 ms, while that corresponding to seepage pores—microfractures is generally larger than 2.5 ms, which matches previous research results. Therefore, in the following comprehensive evaluation of pore—fracture systems, 2.5 ms is taken as the critical value for distinguishing diffusion pores from seepage pores—microfractures. Furthermore, the spectral area enclosed by the spectral peaks and changes in morphology of T2 spectra were used to characterize the percentage of porous volumes of diffusion pores, seepage pores, and microfractures and the connectivity between pores and fractures.

3.1.2. Determination of the Critical Value for Distinguishing Diffusion Pores from Seepage Pores—Microfractures Based on the MIP. For the eight test samples in the MIP experiment, ln p and ln(Dv/dp) were fitted (Figure 4).

As shown in Figure 4, the critical values for distinguishing diffusion pores from seepage pores—microfractures in different coal samples were determined. To be specific, the critical values in coal samples C1-1, C1-2, and C1-3 are 67—72 nm, while those in coal samples C2-1, C2-2, and C2-3 range from 60 nm to 75 nm. Moreover, the critical values in samples P-1 and P-2 are between 66 and 89 nm. Although the critical values for distinguishing diffusion pores from seepage pores in the test coal samples are slightly different, the overall change is small. The average, 72 nm, is taken as the critical value for distinguishing diffusion pores from seepage pores—microfractures in the studied coal samples.

3.2. Comprehensive Evaluation of Pores and Fractures. 3.2.1. Evaluation Results of Development Character-
3.2.1.1. Porous Volumes of Diffusion Pores and Seepage Pores−Microfractures. Based on the MIP test data and Formula 1, porous volumes of diffusion pores and seepage pores−microfractures were calculated by combining with the critical values for distinguishing diffusion pores from pores−microfractures determined by fractal dimensions with the MIP, that is

\[ V_k = \sum_{r=72nm} V_k/m \]
\[ V_s = \sum_{r=72nm} V_s/m \]

where, \( V_k \) and \( V_s \) represent the porous volumes (cm³/g) of diffusion pores and seepage pores, respectively; \( V_k/m \) and \( V_s/m \) separately represent the porous volume (cm³) when the pore throat radius is \( r \) and mass (g) of the coal sample.

The calculated porous volumes of diffusion pores and seepage pores−microfractures in the coal samples are listed in Table 1.

### Table 1. Calculation Results of the Evaluation Parameters of Diffusive Pores and Seepage Pores−Microfractures

| sample number | volumes of pores (cm³/g) | percentages of porous volumes (%) | mercury ejection efficiency (%) | fractal dimensions |
|---------------|--------------------------|-----------------------------------|--------------------------------|-------------------|
|               | A                        | B                                 | A                               | B                 |
| C1-1          | 0.0130                   | 0.0272                            | 98.361                          | 1.639             |
| C1-2          | 0.0136                   | 0.0323                            | 95.123                          | 4.877             |
| C1-3          | 0.0130                   | 0.0296                            | 99.207                          | 0.793             |
| C1-2          | 0.0147                   | 0.0410                            | 97.242                          | 2.758             |
| C1-2          | 0.0122                   | 0.0336                            | 89.361                          | 10.639            |
| C1-3          | 0.0117                   | 0.0369                            | 98.174                          | 1.826             |
| C1-1          | 0.0152                   | 0.0013                            | 28.979                          | 71.021            |
| C1-2          | 0.0162                   | 0.0014                            | 28.697                          | 71.303            |

In the table, A represents the diffusion pores and B represents the seepage pores−microfractures.

3.2.1.2. Percentages of Porous Volumes of Diffusion Pores and Seepage Pores−Microfractures. The area enclosed by different peaks of pores and fractures on T2 spectral curves represents the proportion of such pores or fractures, from which, their percentage porous volumes are

\[ V_i = \sum_{M_i} M_i \times 100\% \]

where, \( V_i \) denotes the percentage of porous volume; \( M_i \) and \( M_t \) are the spectral area corresponding to diffusion pores or
seepage pores—microfractures in the T₂ spectrum and the total spectral area, respectively.

The calculation results of percentages of porous volumes of diffusion pores and seepage pores—microfractures in the coal samples are summarized in Table 1.

3.2.1.3. Mercury Ejection Efficiency. The maximum mercury injection and ejection during the MIP test were obtained, and the mercury ejection efficiency is given by

\[
\eta = \frac{v_2}{v_1} \times 100\%
\]

where, \(\eta\), \(v_2\), and \(v_1\) represent the mercury ejection efficiency, the mercury ejection (cm³/g), and the maximum mercury injection (cm³/g), respectively.

The calculated mercury ejection efficiencies of various coal samples are listed in Table 1.

3.2.1.4. Fractal Dimensions of Diffusion Pores and Seepage Pores—Microfractures. In accordance with Formula 2 and mercury injection data under different injection pressures, the fractal dimensions of diffusion pores and seepage pores in the test samples were calculated (Figure 4). Seepage pores—microfractures with large pore sizes have typically fractal features, and the fractal dimension varies between 2 and 3. Moreover, the degree of fitting exceeds 90%. The degree of fitting for smaller diffusion pores is relatively low and the fractal dimension is between 3 and 4. The reason for this is that the coal matrix is compressed and deformed under high-pressure mercury injection, so the fractal dimension exceeds 3, but it is still an effective index for characterizing pore characteristics.22,24 The calculated fractal dimensions of diffusion pores and seepage pores—microfractures in various coal samples are listed in Table 1.

3.2.2. Evaluation Results of Connectivity Between Diffusion Pores and Seepage Pores—Microfractures.

3.2.2.1. Calculation Results of Pore—Fracture Distribution Uniformity. Volumes of pores of different sizes as measured by MIP change with the pore-throat radius. Pore distributions in the coal samples can be classified into three morphologies, namely, unimodal, crescent, and stepped shapes, as shown in Figure 5.

In coal samples with a crescent-shaped pore distribution, both diffusion pores and microfractures are developed, while seepage pores are not developed. The peak value of diffusion pores is more than 1/3 of the microfractures, and the uniformity of the pore—fracture distribution is medium. Developed microfractures and fewer diffusion pores and seepage pores are found in coal samples with a unimodal pore distribution. The peak value of diffusion pores is less than 1/3 of the microfractures, and the uniformity of the pore—fracture distribution is the lowest. In the coal samples with the...
3.2.2. Characteristic Structural Coefficient. The characteristic structural coefficient is the reciprocal of the product of the coefficient of variation $D_1$ and structural coefficient $\phi_f$. The coefficient of variation (relative sorting coefficient) $D_1$ can be expressed as follows

$$D_1 = \frac{\overline{p}}{\sigma} = \frac{1}{\bar{r}} \sqrt{\frac{\sum (r_i - \bar{r})^2 \times \Delta S_i}{\sum \Delta S_i}} \quad (13)$$

where, $D_1$ indicates the coefficient of variation and is dimensionless; $\bar{S}_p$ and $r_i$ represent the sorting coefficient and pore–throat radius ($\mu$m) at a certain point, respectively; $\bar{r}$ and $\Delta S_i$ denote the average pore–throat radius ($\mu$m) and mercury saturation (%) corresponding to $r_i$ in a certain interval, respectively.

The structural coefficient $\phi_f$ can be expressed as follows

$$\phi_f = \frac{\phi_r (\bar{r})^3}{8K} \quad (14)$$

where, $\phi_{r}, \phi_r, \phi_f$, and $K$ denote the structural coefficient (dimensionless), porosity (%), and air permeability ($\mu$m$^2$), respectively.

The characteristic structural coefficient $C_{sc}$ can be expressed as

$$C_{sc} = \frac{1}{D_1 \phi_f} \quad (15)$$

where, $C_{sc}$ denotes the characteristic structural coefficient.

The calculated characteristic structural coefficients of various coal samples are listed in Table 2.

3.2.2.3. Mercury Saturation. The maximum mercury injection and porosity during the MIP test were obtained, and the mercury injection saturation was calculated thus

$$C = \frac{v_i \rho}{\phi} \times 100\% \quad (16)$$

where, $C$, $v_i$, and $\rho$ denote the mercury injection saturation (%), the maximum mercury injection (cm$^3$/g), and density (g/cc) of coal, respectively.

The calculated mercury saturations of various coal samples are listed in Table 2.

3.2.2.4. Types of $T_2$ Spectra. The width of the NMR spectral peak indicates the quality for sorting of a certain type of pores, and the number of peaks represents the connectivity of pores of different sizes in coal and rock. According to the distribution morphologies of NMR spectral peaks of the studied coal samples, the $T_2$ spectra of the coal samples were classified into three types: unimodal, discontinuous bimodal, and continuous bimodal (Figure 3). The classification of the types of $T_2$ spectra of the coal samples is summarized in Table 2.

3.3. Classification of the Pore–Fracture Combination Types in Tectonic Coal. Based on the established comprehensive evaluation index system for diffusion pores and seepage pores–microfractures in tectonic coal and the parameters of the coal samples tested by NMR and high-pressure MIP tests, the pore–fracture combination types of the studied coal samples were classified, as displayed in Table 4. There are three pore–fracture combination types in the studied coal samples with following characteristics:

3.3.1. High Diffusivity and Permeability and Poor Pore–Fracture Connectivity. In the coal samples, large diffusion pores, and seepage pores, or microfractures are developed, while the lack of seepage pores of medium sizes leads to poor connectivity between pores and fractures of different sizes. A reservoir with such a pore–fracture combination type has a large porosity but average permeability, and gas migration is difficult.

3.3.2. Low Diffusivity, High Permeability, and Good Pore–Fracture Connectivity. In the coal samples, diffusion pores are undeveloped, while seepage pores–microfractures are well developed. Pores and fractures with different sizes are well connected. Gas production in a reservoir with such a pore–fracture combination type is mainly limited by diffusion velocity.
### Table 3. Comprehensive Evaluation Index System for Diffusion Pores and Seepage Pores-Microfractures

| Evaluation Types | Evaluation Indexes | Weight | Evaluation Grades and Scores | Evaluation Principle |
|------------------|--------------------|--------|-----------------------------|----------------------|
| the development of diffusion pores | volumes of pores (cm³/g) | 0.30 | >0.15 | 0.013–0.15 | <0.013 | according to the scores and weights of each parameter, the total score of no less than 2 points is high diffusion/high seepage; good connectivity, scores less than 2 points indicate low diffusion/low seepage/poor connectivity |
| | percentages of porous volumes (%) | 0.25 | >90 | 50–90 | <50 |
| | mercury ejection efficiency (%) | 0.30 | <70% | 70–80% | <80% |
| | fractal dimensions | 0.15 | <3.5 | 3.5–3.7 | >3.7 |
| the development of seepage pores-microfractures | volumes of pores (cm³/g) | 0.40 | >0.03 | 0.01–0.03 | <0.01 |
| | percentages of porous volumes (%) | 0.10 | >50 | 10–50 | <10 |
| | mercury ejection efficiency (%) | 0.25 | <50% | 50–70% | <70% |
| | fractal dimensions | 0.25 | <2.4 | 2.4–2.6 | >2.6 |
| connectivity between pores and fractures | distribution uniformity | 0.20 | stepped | crescent-shaped | unimodal |
| | characteristic structural coefficient | 0.20 | >0.5 | 0.1–0.5 | <0.1 |
| | mercury saturation (%) | 0.30 | >90 | 85–90% | <85% |
| | types of T₂ spectra | 0.30 | continuous bimodal | discontinuous bimodal | unimodal |

### 5. EXPERIMENTAL SECTION

#### 5.1. Experimental Samples

The coal samples used in the experiments were taken from the Changping coal mine, Jincheng city, Shanxi province, Pingdingshan no. 4 mine, Jiaozuo City, Henan Province, and Pingdingshan no. 4 mine, Pingdingshan city, Henan province, China. Blocks measuring 250 x 150 mm were collected from the Changping coal mine, Pingdingshan city, Henan province, and Pingdingshan no. 4 mine, Pingdingshan city, Henan province. Blocks measuring 20 mm x 20 mm were separately drilled to find characteristic structural coefficients and mercury saturation. Parameters, such as pore-pore connectivity, the combination type with high permeability, and good pore-permeability were selected to evaluate the degree of development of diffusion pores and seepage/pore-permeability. A reservoir with such a pore-permeability both in the coal samples have good permeability and gas migration is difficult.

#### 5.2. Equipment

A Model 380011 low-field NMR instrument with a resonant frequency of 21.67568 MHz in Henan Polytechnic University was used. For the instrument, the magnet temperature field intensity was maintained at 32 ± 0.1 T. An Auto Pore IV 9505 automatic mercury permeability and gas migration was performed to determine the critical values of mercury permeability, and gas migration under different conditions.

#### 5.3. Experimental Samples

The studied coal samples can be divided into three types by using the method of pore-pore connectivity and type of T₂ spectra were selected to evaluate the degree of development of diffusion pores and seepage/pore-permeability. A reservoir with such a pore-permeability both in the coal samples have good permeability and gas migration is difficult.

#### 4. CONCLUSIONS

- **3.3.2** Low Diffusivity, Although diffusion pores and seepage pores have good connectivity, both of them are undeveloped. A reservoir with such a pore-permeability both in the coal samples have good permeability and gas migration is difficult.
### Table 4. Classification Results of the Combination Types of Diffusion Pores and Seepage Pores—Microfractures

| Sample Number | Evaluation Types | Evaluation Indexes | C1-1 | C1-2 | C1-3 | C2-1 | C2-2 | C2-3 | P-1 | P-2 |
|---------------|------------------|--------------------|------|------|------|------|------|------|-----|-----|
|               | the development of diffusion pores volumes of pores (cm$^3$/g) | 0.0130 | 0.0136 | 0.0130 | 0.0147 | 0.0112 | 0.0117 | 0.0152 | 0.0162 |
|               | percentages of porous volumes (%) | 98.361 | 95.123 | 99.207 | 97.242 | 89.361 | 98.174 | 28.979 | 28.697 |
|               | mercury ejection efficiency (%) | 70.7692 | 66.1765 | 70.7692 | 61.9048 | 74.1071 | 57.265 | 92.2909 | 85.5848 |
|               | fractal dimensions | 3.6970 | 3.5323 | 3.6497 | 3.6033 | 3.5807 | 3.4666 | 3.8739 | 3.7595 |
|               | the development of seepage pores—microfractures volumes of pores (cm$^3$/g) | 0.0272 | 0.0323 | 0.0296 | 0.0410 | 0.0336 | 0.0369 | 0.0013 | 0.0014 |
|               | percentages of porous volumes (%) | 1.639 | 4.877 | 0.793 | 2.758 | 10.639 | 1.826 | 71.021 | 71.303 |
|               | mercury ejection efficiency (%) | 4.4118 | 8.3591 | 4.3919 | 7.561 | 4.1667 | 6.7751 | 73.9171 | 84.9969 |
|               | fractal dimensions | 2.4570 | 2.4277 | 2.4118 | 2.5265 | 2.3666 | 2.4045 | 2.8203 | 2.7995 |
|               | distribution uniformity characteristic | 0.006 | 0.015 | 0.012 | 0.297 | 0.610 | 1.087 | 0.036 | 0.543 |
|               | structural coefficient | 83.762 | 87.644 | 85.343 | 92.413 | 86.279 | 89.625 | 85.487 | 85.281 |
|               | mercury saturation (%) | unimodal | discontinuous bimodal | unimodal | unimodal | unimodal | unimodal | continuous bimodal | continuous bimodal |

| Sample Number | Evaluation Types | Evaluation Indexes | C1-1 | C1-2 | C1-3 | C2-1 | C2-2 | C2-3 | P-1 | P-2 |
|---------------|------------------|--------------------|------|------|------|------|------|------|-----|-----|
|               | types of diffusion pores high diffusion | high diffusion | high diffusion | high diffusion | high diffusion | low diffusion | high diffusion | low diffusion | low diffusion |
|               | types of seepage pores—microfractures high seepage | high seepage | high seepage | high seepage | high seepage | high seepage | low seepage | low seepage |
|               | types of connectivity poor connectivity | poor connectivity | poor connectivity | poor connectivity | poor connectivity | good connectivity | poor connectivity | good connectivity |
|               | comprehensive evaluation results | X | X | X | Y | X | Z | Z |

In the table, X represents the pore—fracture combination type of high diffusivity and permeability and poor pore—fracture connectivity, Y represents the pore—fracture combination type of low diffusivity, high permeability, and good pore—fracture connectivity, and Z represents the pore—fracture combination type of low diffusivity and permeability and good pore—fracture connectivity.
porosimeter was used in the high-pressure MIP experiment. The instrument was suitable for measuring pore size distribution, total porous volume, total specific surface area of pores, and the pore size in the range of 5.5 nm−360 μm.

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**Notes**
The authors declare no competing financial interest.

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