Investigating the Fractal Characteristics of Pore-Fractures in Bituminous Coals and Anthracites through Fluid Flow Behavior

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ABSTRACT: The characteristics of pore-fractures are the key petrophysical properties used to assess and evaluate coalbed methane (CBM) reservoirs and include pore types, structure types, porosity/percentage, and pore-fracture space properties. To study the storage and seepage capability of a CBM reservoir, based on 18 coal samples with the maximum vitrinite reflectance ($R_o,max$) in the range of 1.06–3.04%, we used the nuclear magnetic resonance (NMR) method and fractal analysis to investigate the effect of coalification on the characteristics of pore-fractures. First, the pore-fracture space in a coal reservoir includes irreducible fluid space and moveable fluid space. We built up the moveable fluid NMR fractal based on the saturated/irreducible fluid NMR fractals. Saturated fluid fractal ($D_o$), irreducible fluid fractal ($D_i$), and moveable fluid fractal ($D_m$) have the following relationship: $D_m > D_o > D_i$. Additionally, $D_o$ has a huge fluctuating value area with the maximum vitrinite reflectance ($R_o,max$) varying between 1.93% and 2.06%. The curve $lg(T_2)$ and $lg(V)$ for a moveable fluid fractal has four typical types. The shapes “C”, “Z”, “S”, and “T” correspond to four structure types (A, B, C, and D), which provide significant guidance for CBM exploitation. Moreover, the saturated-irreducible $T_2$ distribution has a special shape, known as the pendular ring, which affects the seepage ability and permeability. Second, we classify the pore-fracture types based on the saturated fluid NMR fractal and the $T_2$ distribution as follows: adsorbed pore ($T_2 < 0.4$ ms, $10^{-10}$ nm), transition pore ($T_2 = 0.4–2.5$ ms, $10^{-10}$–$10^{-8}$ nm), seepage pore ($T_2 > 2.5$ ms, $> 100$ nm). At $R_o,max = 1.06–3.04%$, the percentages of pore-fracture types show that coalification has three coalification jumps at $R_o,max = 1.3%$, 2.0%, and 2.8%. The porosities of pore-fracture types show that the thermal volatilization of fillers in pore-fractures begins at $R_o,max = 1.5$% and disappears at $R_o,max = 2.5%$. Different fluid space fractals demonstrate that when $R_o,max < 2.0%$, the coal reservoir tends to be compressed and consolidated, whereas when $R_o,max > 2.0%$ the coal reservoir tends to be orderly and uniform. BVM/BVI is the ratio of the irreducible fluid space (BVI) and the movable fluid space (BVM). Finally, the permeability indicates a positive exponential function with BVM/BVI for seepage pores, and it exhibits a negative exponential function with BVM/BVI for adsorbed pores and transition pores. The NMR method combining fractal analysis with coalification enables us to characterize pore-fractures and the effects of coalification on pore-fractures quantitatively, which contributes to guiding CBM exploitation. Moreover, the relationship between permeability and BVM/BVI is beneficial for predicting the favorable areas for CBM exploitation.

1. INTRODUCTION

Coal reservoirs store an abundance of an alternative fossil source called coal bed methane (CBM), which can be used to support the development of social economies. The dual pore-fracture system in a coal reservoir is the main CBM enrichment space and migration channel. CBM capacity and production are unstable because of complex pore-fracture characteristics and are affected by geothermal dynamics and the buried depth of the coal seam. The pore-fracture characteristics are discontinuous, heterogeneous, and anisotropic. The characteristics include pore-fracture structure, shape, and the connection network that affects the processes of gas adsorption, desorption, and migration. Investigating the storage capacity and transport mechanisms of pore-fractures in coal reservoirs has great significance for characterizing coal reservoirs.

To investigate the effects of the pore-fractures characteristics on CBM exploitation qualitatively, multiple classifications of pore-fracture systems have been established and adopted. Hodot’s classification based on pore size is widely used and is categorized as follows: micropore ($<10$ nm), transition pore ($10–100$ nm), mesopore ($10^{-10}$–$10^{-8}$ nm), macro pore ($10^{-8}$–$10^{-6}$ nm), and fracture ($>10^{-6}$ nm). However, Hodot’s classification cannot describe the pore-fractures accurately and comprehensively due to the complexity and randomness of the distribution of the pore-fractures. Yao et al. classified pore-fractures based on the gas adsorption–desorption as adsorbed pores and seepage pores. Salazar et al. classified pore-fracture spaces based on stored fluid characteristics as moveable fluid space and irreducible fluid space. This paper studies the pore-fractures in coal reservoirs mainly based on Yao and Salazar’s classifications.

A coal reservoir is a pressure-sensitive, porous material with complex surface morphology. Scholars have introduced many methods and technologies to study pore-fractures in coal reservoirs, such as MIP (mercury intrusion), $N_2$ adsorption/desorption, SEM (scanning electron microscopy), and small-angle X-ray scattering. These methods and technologies may destroy the coal matrix system, narrow the pore size, and lose parts of important details about the coal reservoir. Therefore, seeking a nondestructive, accurate, and efficient method is also a main research goal. As it is a rapid, accurate, nondestructive, and high resolution method, the NMR technique is widely used to investigate the petrophysical characterization, size, shape, and porosity of pore-fractures.
Table 1. Sampling Location, Coal Rank, Porosity, and Permeability for Samples

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Vitrinite reflectance ($R_{0,max}$, %)</th>
<th>Coal seam no.</th>
<th>Coal bearing strata</th>
<th>Sample location</th>
<th>N</th>
<th>E</th>
<th>Porosity (%)</th>
<th>Permeability (mD)</th>
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<td>0.01704</td>
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</table>

2. MATERIALS AND METHODS

2.1. Sampling Methods. Eighteen coal samples were collected from the Xishan coalfield, which was one of major CBM enrichment coalfields in China. The Pennsylvanian Taiyuan formation and the Lower Permian Shanxi formation are the coal-bearing strata. All of the samples were large blocks (approximately 20 cm x 30 cm x 30 cm) collected from these two formations in accordance with the Chinese Standard Method GB/T 19222–2003 and were carefully wrapped, transported, and immediately delivered to the laboratory for experiments. All information for these samples is listed in Table 1.

2.2. Experiment. A series of experiments and analyses were carried out on each of the collected samples, including vitrinite reflectance ($R_{0,max}$), permeability, porosity, and NMR measurements. Vitrinite reflectance, permeability and porosity analyses were conducted in accordance with previous research following the China National Standards GB/T 6948-1998, GB/T 212-2001, and SY/T 336-1996. From these coal blocks, one or more horizontal cylindrical core plugs (2.5 cm in diameter) were drilled for the purpose of NMR measurement. Two sets of NMR measurements were performed: one at a 100% water-saturated condition ($S_w$) and another at an irreducible water condition ($S_i$) used to simulate the total pore-fracture space and the irreducible fluid space, respectively. For the saturated water condition, all core plugs were dried at 100 °C for at least 24 h in a vacuum oven and were subsequently saturated with 100% distilled water for another 24 h. Core plugs at the saturated water condition were analyzed in the NMR experiment and were transferred to the centrifugal experiment for the irreducible water condition. The centrifugal experiment was conducted in a PC-1 Petroleum Core Centrifuge. The centrifugal speed was set at 6000 r/min in order to obtain an ideal irreducible water condition. All core plugs in the irreducible water condition were also analyzed in the NMR experiment.

The NMR experiment was carried out using the AniNMR rig in the reservoir laboratory of the China National Engineering Research Center of CBM Development & Utilization.

2.3. NMR Fractal Theory. NMR fractal theory is proposed to confirm the pore-fractures’ geometric characteristics. Generally, NMR experiments have two sets: a saturated water condition and an irreducible water condition. The NMR fractal dimensions are acquired according to the NMR data in the
saturated water condition and the irreducible water condition.12,14,42

Saturated water condition
\[ \log(V_{pw}) = (3 - D_u) \log(T_2) + (D_u - 3) \log T_{2\text{max}} \] (1)

Irreducible water condition
\[ \log(V_{pir}) = (3 - D_u) \log(T_2) + (D_u - 3) \log T_{2\text{max}} \] (2)

Where \( V_{pw} \) and \( V_{pir} \) are the cumulative porosity percentage in the saturated water condition and the irreducible water condition; \( T_2 \), \( T_{2\text{max}} \) are the transverse relaxation time and the maximal transverse relaxation time, respectively; and \( D_u \), \( D_m \) are the NMR fractal dimensions for the saturated water condition and the irreducible water condition.

According to the works of Perfect43 and Coates et al.,44 \( V_{pir} \) can be calculated based on the NMR \( T_2 \) distribution.

\[
\frac{V_{pir}}{V_{pw}} = \frac{V_2}{V_1} \times \frac{V_2}{V_1} \times \phi
\]

Where, \( \phi \) is the percentage of the irreducible fluid.

The saturated water condition and the irreducible water condition are used to study the total pore-fractures’ characteristics and the pore-fractures’ irreducible space characteristics, respectively. The fluid that exists in pore-fractures is irreducible fluid and moveable fluid. To acquire the fractal dimension for the moveable fluid space, we modified eqs 1 and 2.

Using eq 2 - eq 1
\[ \log(V_{pir}/V_{pw}) = (D_u - D_m) \log(T_2) + (D_u - 3) \log T_{2\text{max}} \] (3)

Transform eq 3:
\[ \log(v) = (D_m - 3) \log(T_2) + (D_u - 3 - D_m) \log T_{2\text{max}} + K \] (4)

Where \( v = V_{pir}/V_{pw} \), \( K \) is a constant, decided by \( \phi, D_u, D_m \), and \( D_m \) is the NMR fractal dimension for the moveable fluid.

3. RESULTS

3.1. Basic Information and NMR \( T_2 \) Distribution. The results for the vitrinite reflectance, porosity, and permeability are summarized in Table 1. \( R_{0\text{max}} \) ranges from 1.06% to 3.04%. The porosity and the permeability varied from 0.13% to 15.87%, and 0.00713 to 0.3856 mD, respectively. We acquired the NMR \( T_2 \) distribution at the saturated water condition and the irreducible water condition (Figure 1a). Theoretically, the pore-fracture spaces are occupied by the irreducible fluid and the moveable fluid.15 The NMR \( T_2 \) distributions at the saturated water condition and the irreducible condition were interpreted as the total pore-fractures characteristics and the irreducible fluid space characteristics, respectively. In Figure 1a, the dark gray characterizes the irreducible space, and the light gray characterizes the moveable water. According to previous research,12,45,46 we calculated the cumulative porosity at two conditions, \( T_{2\text{max}} \) and BVM/BVI based on the NMR theory (Figure 1b), and the results are shown in Table 2. \( T_{2\text{max}} \) is a relaxation time threshold that divides the \( T_2 \) relaxation time into two segments: the irreducible fluid space (BVI) and the moveable fluid space (BVM).15 The BVM/BVI index can reflect the connectivity and the seepage property. The larger the BVM/BVI index, the better the connectivity and seepage property. In saturated water conditions, the NMR \( T_2 \) distribution has two or three peaks, and the midcourt line of first peak is at the \( T_2 \) value = 0.4 ms.

3.2. NMR Fractal Dimension. According to the NMR \( T_2 \) distribution and fractal theory (eqs 1, 2, and 4), we calculated the three fractal dimensions \( D_u, D_m \) and \( D_m \) (Figure 2). \( D_u \) reflected the total pore-fractures characteristics, \( D_m \) reflected the...
irreducible fluid characteristics, and $D_M$ reflected the moveable fluid characteristics. These NMR fractal dimensions were shown for different samples in Table 3 and Figure 3. $D_w$ ranges from 2.24 to 2.38, $D_M$ ranges from 2.29 to 2.89, and $D_{ir}$ mainly ranges from 2.75 to 3.07. Meanwhile, $D_{ir}$ has a huge fluctuating value area of $R_{o,max} = 1.93−2.06\%$. The change may be attributed to the third coalification jump; more details for this interpretation are provided in the following discussion.

### Table 3. Fractal Dimensions for Different NMR Conditions

<table>
<thead>
<tr>
<th>sample no.</th>
<th>$D_{ir}$</th>
<th>$R^2$</th>
<th>$D_w$</th>
<th>$R^2$</th>
<th>$D_M$</th>
<th>$R^2$</th>
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<td>0.39</td>
<td>2.85</td>
<td>0.83</td>
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<td>2.44</td>
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<td>0.92</td>
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### 3.3. Pore-Fractures Identified by T$_2$ Spectra

The $T_2$ distribution characteristics, including the number, area and peak position, can be used to analyze coal pore-fracture types. According to previous research\textsuperscript{14,22,48}, pore-fractures can be divided into three types based on adsorption−desorption characteristics: adsorbed pore ($T_2 < 2.5$ ms), seepage pore ($T_2 = 2.5−100$ ms), and fracture ($T_2 > 100$ ms). However, the definition cannot reflect the real features of the pore-fractures. Based on the NMR saturated water condition (it was shown by the black solid curve in Figure 2a), the $\lg(T_2)$ and $\lg(V_p)$ can be divided into three segments by the $\lg(T_2)$ value (<−4.5, −4.5 to −3.5, and >−3.5) that correspond to the $T_2$ value (<0.4, 0.4−2.5, and >2.5 ms) and represent the different pore−fractures: adsorbed pore (<0.4 ms, <10 nm), transition pore (0.4−2.5 ms, 10−100 nm), and seepage pore (>2.5 ms, >100 nm)\textsuperscript{17,12,22} (Figure 1a). The porosity of the pore-fractures is proportional to the cumulative signal amplitude of the NMR $T_2$ distribution.\textsuperscript{49} By combining the total porosity with the irreducible water $T_2$ distribution and the saturated water $T_2$ distribution, we calculated the percentage, porosity, and BVM/BVI of different pore-fractures. These results are shown in Table 4.

### 4. DISCUSSION

#### 4.1. Relations among Fractal Dimensions at Different NMR Conditions

As shown in Figure 3, there exists a relationship of $D_M > D_{ir} > D_w$. In pore-fractures, the water existence is in the form of water molecules, and the surface of pore-fractures is a water-absorbing layer\textsuperscript{50,51}. Fractal theory reflects the surface/volume morphology characteristics of pore-fractures. The more complicated the surface/volume morphol-
Ongoing, the results are shown in Table 4. The BVM/BVI value for sample QJ3, TDS, and TL8 is lacking. The reason is that the existence of a pendular ring affects the seepage ability and reduces the permeability (Figure 4). In a normal situation, the signal amplitude of the \( T_2 \) distribution on the saturated water situation is higher than the signal amplitude of the irreducible water situation. However, in Figure 4, we can determine that the signal amplitude of the \( T_2 \) distribution on the saturated water situation is lower than the signal amplitude on the irreducible water situation. This phenomenon is called the "pendular ring" and it appears in the short relaxation time \((T_2 < 2.5 \text{ ms})\). The signal amplitude of the \( T_2 \) distribution is proportional to the pore-fracture's volume, and the relaxation time \( T_2 \) is proportion to the pore size of the pore-fractures.

4.2. Effects of Pendular Ring on Pore-Fracture Permeability. In Table 4, the BVM/BVI value for sample QJ3, TDS, and TL8 is lacking. The reason is that the existence of a pendular ring affects the seepage ability and reduces the permeability (Figure 4). In a normal situation, the signal amplitude of the \( T_2 \) distribution on the saturated water situation is higher than the signal amplitude of the irreducible water situation. However, in Figure 4, we can determine that the signal amplitude of the \( T_2 \) distribution on the saturated water situation is lower than the signal amplitude on the irreducible water situation. This phenomenon is called the "pendular ring" and it appears in the short relaxation time \((T_2 < 2.5 \text{ ms})\). The signal amplitude of the \( T_2 \) distribution is proportional to the pore-fracture's volume, and the relaxation time \( T_2 \) is proportion to the pore size of the pore-fractures.

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water is two large peaks. The $T_2$ distribution for the irreducible water has two peaks: the first is large, and the second is small. The structure type A is good for gas seepage, but is bad for gas enrichment and recovery.

The structure type B is represented by the sample DP7, which has better permeability ($K = 0.3856$ mD), high porosity ($\phi = 15.87\%$), and good connectivity (BVM/BVI = 4.79). The vitrinite reflectance for structure type B is about $R_o,max \approx 1.50\%$. The $T_2$ distribution for the saturated water has three peaks: the first is large, the second and the third are small. The $T_2$ distribution for the irreducible water has two peaks: the first is large, and the second is small. The structure type B is good for gas seepage, gas enrichment, and recovery.

The structure type C is represented by the sample DE10, which has the lowest permeability ($K = 0.0071$ mD), low porosity ($\phi = 1.38\%$), and poor connectivity (BVM/BVI = 1.20). The vitrinite reflectance for structure type C is about $R_o,max \approx 1.90\%$. The $T_2$ distribution for the saturated water has three peaks: the first is large, and the second and the third are small. The $T_2$ distribution for the irreducible water has two peaks: the first is large, and the second is small. The structure type C is bad for gas seepage, gas enrichment, and recovery.

The structure type D is represented by the sample CY13, which has low permeability ($K = 0.1173$ mD), high porosity ($\phi = 10.46\%$), and better connectivity (BVM/BVI = 13.59). The vitrinite reflectance for structure type D is about $R_o,max \approx 2.00\%$. The $T_2$ distribution for the saturated water has three peaks: the first is large, the second and the third are small. The $T_2$ distribution for the irreducible water has two peaks: the first is medium, and the second is large. The $T_2$ distribution for the saturated water has three peaks: the first is large, the second and the third are small. The $T_2$ distribution for the irreducible water has two peaks: the first is medium, and the second is large.

Figure 5. Four typical types (the shape “C”, “Z”, “S”, and “T”) of the curves $\lg(T_2)$ and $\lg(V)$ for moveable fluid NMR fractal analysis, corresponding to the four structure types: A, B, C, and D.

Figure 6. NMR $T_2$ distribution for the four structure types (A, B, C, and D) based on the curves $\lg(T_2)$ and $\lg(V)$ for moveable fluid NMR fractal analysis.
The $T_2$ distribution for the saturated water has three peaks: the first is large, and the second and the third are small. The $T_2$ distribution for irreducible water has two peaks: the first is medium, and the second is small. The structure type D is good for gas enrichment and recovery but is bad for gas seepage.

4.4. Effects of Coalification on Percentage and Porosity of Pore-Fractures. $R_{\text{omax}}$ is considered to be an important index that reflects coalification progress and affects the pore-fracture structure of coal. Figure 7 shows the relationship between the percentage and the porosity of different pore-fractures and $R_{\text{omax}}$. The influences of coalification on the percentage of different pore-fractures are different from the influences on the porosity. The influence of coalification on the percentage and porosity are nonlinear, and coalification has turning points. Previous research discovered that coalification had four turning points, called coalification jumps: the first one is $R_{\text{omax}} = 0.6\%$, the second is $R_{\text{omax}} = 1.3\%$, the third is $R_{\text{omax}} = 2.0\%$, and the fourth is $R_{\text{omax}} = 3.0\%$.28,30

The second and the third are confirmed by the discovery, but the fourth should be $R_{\text{omax}} = 2.8\%$ and not $R_{\text{omax}} = 3.0\%$ (Figure 7).

When $R_{\text{omax}} = 1.0−1.3\%$, as $R_{\text{omax}}$ increases, the percentages of adsorbed pores and transition pores decrease, the percentage of seepage pore increases, and the porosities of the three pore-fracture types decrease. The coal reservoir is at the second coalification jump and is relatively loose.12,23,36 Overburden pressure on the coal reservoir is at low stress, and the coal reservoir is dominated by seepage pores (Figure 7c). As $R_{\text{omax}}$ increases, overburden pressure increases and compresses the coal reservoir. The porosities of the three pore-fracture types decrease. Due to the differences in pore size, the porosities of adsorbed pores and transition pores decrease faster than that of seepage pores. Therefore, the percentage of seepage pores increases and the percentages of adsorbed pores and transition pores decrease.

When $R_{\text{omax}} = 1.3−2.0\%$, as $R_{\text{omax}}$ increases, the percentages of adsorbed pores and transition pores increase, the percentage of seepage pores decreases, the porosity of transition pores increases, the porosities of adsorbed pores and seepage pores first decrease and later increase, and the turning point is at $R_{\text{omax}} = 1.5\%$ (Figure 7). The coal reservoir is at the third coalification jump, and the overburden pressure on the coal reservoir is strengthened to medium pressure. As $R_{\text{omax}}$ increases, overburden pressure compresses and solidifies the coal reservoir. The percentages of adsorbed pores and transition pores increase, therefore the seepage pore percentage decreases. Gradually, the percentage of adsorbed pores becomes 15−40%, the percentage of transition pores becomes 15−30%, and the percentage of seepage pores becomes 70−30%. The percentages of the three pore-fracture types are approximately equal in the coal reservoir (Figure 7a−c), the porosities of adsorbed pores and seepage pores decrease, and the decrease in porosity of seepage pores results in the increase of porosity for transition pores. When $R_{\text{omax}} = 1.5\%$, the volatile fillers in the primary pore-fractures are volatilized because of the changes of temperature, the porosity of adsorbed pores and seepage pores increase.57

When $R_{\text{omax}} = 2.0−2.8\%$, as $R_{\text{omax}}$ increases, the percentages of adsorbed pores and transition pores decrease, the percentages of seepage pores increases, the porosity of transition pores decreases, the porosities of adsorbed pores and seepage pores first increase and subsequently decrease, and the turning point is at $R_{\text{omax}} = 2.5\%$ (Figure 7). The coal reservoir is at the fourth coalification jump, and the overburden pressure on the coal reservoir is further strengthened to high pressure. As $R_{\text{omax}}$ increases, the coal reservoir is compressed and sustains certain damage, and the percentage and the porosity of seepage pores increase. Therefore, the percentages of adsorbed pores and transition pores decrease. The decrease of porosity in transition pores results in the increase of adsorbed pores. Gradually, the percentage of seepage pores becomes 30−55% and becomes the main pore-fracture type in the coal reservoir (Figure 7c). When $R_{\text{omax}} = 2.5\%$, the volatile fillers in the primary pore-fractures have nearly disappeared, and the porosities of adsorbed pores and seepage pores decrease.58,60 Therefore, the thermal volatile fillers have a significant influence on the porosity of pore-fractures.

When $R_{\text{omax}} > 2.8\%$, as $R_{\text{omax}}$ increases, the percentages of adsorbed pores and seepage pores decrease, the percentage of transition pores increases, the porosities of adsorbed pores and seepage pores decrease, and the porosity of transition pores increase (Figure 7). The overburden pressure on the coal reservoir is at extremely high pressure, which indicates that the coal reservoir does not belong to the coalification stage.60,61 High pressure makes the percentages and porosities of seepage pores and adsorbed pores decrease, and the percentage and porosity of transition pores increases. The percentage of
transition pores is 15–65%, and it becomes the main pore type in the coal reservoir (Figure 7b).

4.5. Effects of Coalification on Different Pore-Fractures’ Fluid Spaces. Pore-fractures in coal reservoirs are filled with fluid, and the characteristics of pore-fractures include the total space, the irreducible fluid space, and the moveable fluid space. Figure 8 shows the relationship between different pore-fractures’ fluid spaces and $R_{o,max}$. When $R_{o,max} = 1.0–3.0\%$, as $R_{o,max}$ increases, $D_o$ for total space and $D_M$ for moveable fluid space first increase and then decrease, the turning point at $R_{o,max} = 2.0\%$, and $D_o$ for irreducible fluid space decreases, but there is a huge fluctuating value at $R_{o,max} = 2.0\%$. It is the third coalification jump point at $R_{o,max} = 2.0\%$.

When $R_{o,max} < 2.0\%$, the overburden pressure on the coal reservoir is at low-medium pressure. The coal reservoir is relatively loose, coalification mainly compresses and solidifies a coal reservoir. Pore-fractures are mainly adsorbed pores and seepage pores (Figure 7a and c). Looser structure, greater percentages of adsorbed pores, and seepage pores result in a more irregular and corrugated surface of the porous medium. The total space and moveable fluid space become complex, and the porosities for total space and moveable fluid space are characterized by a lack of regularity and scatterplots (Figure 8b and f). Therefore, $D_o$ and $D_M$ increase along with increasing $R_{o,m}$ (Figure 8a and e); the percentage of irreducible fluid space in the total pore-fractures is notably small and is sensitive to pressure. As $R_{o,max}$ increases, the irreducible pore space is compressed and decreases (Figure 8d), and the volume of the irreducible fluid space decreases. Therefore, $D_o$ decreases with increasing $R_{o,max}$ (Figure 8c).

When $R_{o,max} > 2.0\%$, the overburden pressure on the coal reservoir is at high and extremely high pressure, and the thermal volatile fillers in the coal reservoir have nearly disappeared. The coal reservoir tends to be orderly, and the pore size tends to be uniform. The connectivity of the pore-fractures becomes good, and the complexity decreases.

Therefore, $D_o$, $D_M$, and $D_M$ also decrease with increasing $R_{o,max}$ (Figure 8a, c, and e).

4.6. Relations between Permeability and BVM/BVI for Typical Pores. BVM/BVI is the ratio of the moveable space porosity and the irreducible space porosity and is used to characterize the connectivity and permeability of the pore-fractures. The permeability shows a positive exponential function with BVM/BVI for seepage pores, and shows a negative exponential function with BVM/BVI for adsorbed pores and transition pores (Figure 9). Generally, the larger value of BVM/BVI is indicative of more moveable space porosity and less irreducible space porosity, which means it has better connectivity and higher permeability. The values of BVM/BVI for seepage pores conform to this law; however, the value of BVM/BVI for adsorbed pores and transition pores do not conform to this law. Because all pore-fractures are centrifuged simultaneously, the irreducible space exists in the three pore types: adsorbed pore, transition pore, and seepage pore. Therefore, the signal amplitude of the irreducible space for seepage pores overlays that of adsorbed pores and transition pores. The pore fluid is arranged layer-by-layer and flows from small pore to large pore. The difference of the adsorption property in two pore types will affect and hinder the pore fluid flow. The more signal amplitude of irreducible space from seepage pores overlays the adsorbed pores and transition pores, the smaller the value of BVM/BVI for adsorbed pores and seepage pores. Therefore, the better the permeability, the larger the BVM/BVI for adsorbed pores and transition pores.

5. CONCLUSIONS

In this paper, we established the moveable fluid space fractal based on the saturated fluid and irreducible fluid fractals, and we investigated the characteristics of pore-fractures in bituminous coals and anthracites through fluid flow behavior by the three NMR fractals. The study’s conclusions are summarized as follows.
Relation between permeability and BVM/BVI for different pore types. BVM/BVI is the ratio of the moveable space porosity and the irreducible space porosity for different pore types.

1. $D_s$ for the saturated fluid, $D_w$ for the irreducible fluid, and $D_M$ for the moveable fluid have the relationship: $D_M > D_s > D_w$. The relationship for the three NMR fractals is affected by the fluid space surface morphology. The pendular ring in the saturated-irreducible $T_2$ distribution affects the seepage ability and reduces the permeability.

2. The curve for the moveable fluid fractal has four types. The shapes C, Z, S, and T correspond to four structure types: A, B, C, and D. The structure type B is good for CBM exploitation; the structure type C is unfavorable for CBM exploitation.

3. The pore-fracture types include the adsorbed pore ($T_2 < 0.4$ ms, $< 10$ nm), the transition pore ($T_2 = 0.4$ to $2.5$ ms, $10$ to $100$ nm), and seepage pore ($T_2 > 2.5$ ms, $> 100$ nm). The second coalification jump decreases the percentage of seepage pores, the third coalification jump makes the three types approximately equal, and the fourth coalification jump makes transition pores the main type. The thermal volatilization of fillers in pore-fractures increases the porosities of adsorbed pores and seepage pores.

4. As $R_{o,max}$ increases, $D_s$ for the total space and $D_M$ for the moveable fluid space first increase and then decrease; $D_w$ for the irreducible fluid space decreases. The turning point is at $R_{o,max} = 2.0%$. The permeability exhibits a positive exponential function with BVM/BVI for seepage pores and exhibits a negative exponential function with BVM/BVI for adsorbed pores and transition pores.

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