A novel pore size classification method of coals: Investigation based on NMR relaxation

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1. Introduction

High-efficiency coalbed methane (CBM) development is of importance in some countries (e.g., Australia, Canada and China) since it can better decrease greenhouse gas emissions, ensure coal production safety, and provide clean energy (Karacan et al., 2011; Moore, 2012). The rapid development of CBM industry has drawn much attention to coal petrophysical property investigations, like pore fluid characterization, pore size distribution (PSD), wettability and permeability (Weniger et al., 2012; Zhao et al., 2017; Du et al., 2019; Yao et al., 2019). The PSD is one of the important parameters to comprehensively analyze the flow and storage capacities of gas and water in coal, and the prediction of CBM production (Close, 1993; Clarkson and Bustin, 1999). Thus, an accurate quantitative characterization of the PSD in coals is key for CBM production.

Currently, various updated methods have been used to characterize coal PSD, such as imaging analysis methods, fluid intrusion methods and nonintrusive fluid methods. Image analysis methods include high resolution scanning electron microscope (SEM), atomic force microscopy (AFM) and transmission electron microscopy (TEM). Fluid intrusion methods, including mercury intrusion porosity (MIP) and gas adsorption (N\textsubscript{2} and CO\textsubscript{2}). Nonintrusive fluid methods, including X-ray computerized tomography (X-CT) and small-angle neutron scattering (SANS). However, some of these methods have certain limitations in...
While MIP measurement is generally used to analyze meso-pores and example, Sun et al. (2018) investigated the wettability changed of 2006; Rezaee et al., 2012; Sulucarnain et al., 2012; Yao et al., 2014; destroy the micro-pore structure of coal (Friesen and Mikula, 1988; Yao of macro-pores and fractures in coal (Hassan, 2012; Chen et al., 2018). Gas adsorption method only can reflect the information only reflect the local information of pore structures (Nie et al., 2015; Liu characterization coal pores. For example, image analysis methods can add the micro-pores and macro-pores because of the high pressure of intrusion mercury can destroy the micro-pore structure of coal (Friesen and Mikula, 1988; Yao and Liu, 2012; Li et al., 2015; Gao et al., 2018).

Recently, nuclear magnetic resonance (NMR) method serves as an accurate technique to evaluate petrophysical properties of porous medium, like wettability, PSD, permeability and so on (Al-Mahrooqi et al., 2006; Rezaee et al., 2012; Sulucarnain et al., 2012; Yao et al., 2014; Liang et al., 2019; Su et al., 2018; Li et al., 2019; Lyu et al., 2019). For example, Sun et al. (2018) investigated the wettability changed of CO2-water in coals by NMR measurement and found CO2 can reduce the water wettability. An absolute and accurate PSd can be obtained from the NMR T2 distribution using centrifugal experiment method and surface relaxivity method (Saidian and Prasad, 2015; Zheng et al., 2019a, b). Based on the results of fully-saturated NMR T2 distribution, the pores in coal were classified into three types: adsorption-pore (T2 < 2.5 ms), seepage-pore (2.5 ms < T2 < 50 ms) and fracture (T2 > 100 ms) (Yao et al., 2018b). In addition, according to the shape of T2 spectra, the connectively characteristics of rocks can also be estimated. Continuous T2 spectrum usually reflects good connectivity among different pores, whereas discontinuous T2 spectrum indicates the poor connectivity (Yao et al., 2010).

NMR T2 cutoff value (T2C), a key NMR measurement parameter that defined the movable and irreducible-water pore, and it is also an important determined parameter for evaluating permeability and full-scale PSD (Ge et al., 2015a, b; Xu et al., 2017). Conventionally, default values such as 33 and 90 ms are often chosen for sandstone and carbonate, respectively (Timur, 1969; Coates et al., 1999). However, unlike the conventional reservoirs, many researchers found that the T2C of unconventional reservoirs shows a large deviation. For instance, Yao et al. (2010) determined the T2C of coals range from 2.5 to 32 ms. Liu et al. (2018b) suggested the T2C value in Lower Silurian Longmaxi shales in the range of 0.45–2.98 ms. Possibly because of the more complicated and heterogeneity pore structure characterization in coals and shales than those in conventional reservoirs.

For NMR pore size classification, the most commonly used method is dividing a fully-saturated T2 spectrum into two parts based on the determined T2C: T2 > T2C for the free fluid parts corresponds to free fluid pores, T2 < T2C for the irreducible fluid parts corresponds to irreducible fluid pore (Ge et al., 2015a, b; Zhang et al., 2018). In this study, we defined this pore classification standard as single T2 cutoffs model. However, when we tried to apply this model to distinguish the movable and irreducible fluid pores, we found that when T2 > T2C, there is still some irreducible fluid after high pressure centrifugal experiments. In addition, there is still some movable fluid when T2 < T2C. Thus, the pore classification determined by single T2 cutoffs model cannot accurately describe the pores with different fluid characteristics. Liu et al. (2018b) and Yuan et al. (2018) classified the shale pores into unrecoverable, capillary bound and movable fluid-pores based on dual T2 cutoffs which combined centrifugal and heat-treated measurements. However, the heat-treated experiments may destroy the organic matter in coals which cannot reflect the real coal PSDs. Fan et al. (2018) and Liu et al. (2018a) proposed a novel pore types classification in tight sandstones only depended on NMR centrifugal experiments, which divided the pores into absolute irreducible pores, absolute movable pores and partial movable pores. It should be noticed that the T2 distributions of coals usually characterized by a tri-modal, that are different from sandstones that having typical bimodal distribution in Fan et al. (2018) and Liu et al. (2018a). In this study, fifteen coal samples with different ranks were collected and performed for a series of NMR and centrifugal measurements. After that, the shortcomings of single T2 cutoffs model in pore fluid distinguishing were investigated. Finally, we introduced a novel method for accurate classification of pore fluid size in coals.

### 2. Samples and experiments

#### 2.1. Samples

Fifteen coal samples with the different coal ranks were collected from the Junngar basin and Qinshui basin. The basic information for those samples, including the mean maximum vitrinite reflectance (Rm), coal maceral composition, and proximate analysis are listed in Table 1. The coals are subbituminous to anthracite, with a wide range of Rm from 0.52% to 3.07%. Vitrinite contents of coals vary from 50.2% to 90.4%, adhesive moisture (air-dried basis); A4 = ash (dry basis); V4 = volatile (dry, ash free basis); FC4 = carbon (air-dried basis).

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Rm (%)</th>
<th>V (%)</th>
<th>I (%)</th>
<th>E (%)</th>
<th>M (%)</th>
<th>Proximate analysis (%)</th>
</tr>
</thead>
<tbody>
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<td>#1</td>
<td>0.52</td>
<td>64.3</td>
<td>30.7</td>
<td>4.7</td>
<td>0.3</td>
<td>7.67, 21.34, 33.71, 44.95</td>
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<tr>
<td>#2</td>
<td>0.63</td>
<td>75.6</td>
<td>22.7</td>
<td>0.3</td>
<td>0.4</td>
<td>12.68, 3.52, 25.81, 71.04</td>
</tr>
<tr>
<td>#3</td>
<td>0.69</td>
<td>77.4</td>
<td>16.5</td>
<td>5.8</td>
<td>0.3</td>
<td>2.55, 5.37, 37.37, 57.26</td>
</tr>
<tr>
<td>#4</td>
<td>0.71</td>
<td>65.6</td>
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<td>0.3</td>
<td>0.1</td>
<td>7.36, 1.15, 27.81, 71.04</td>
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<td>50.2</td>
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<td>7.9</td>
<td>2.70, 15.49, 28.09, 56.42</td>
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<td>54.0</td>
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<td>0.88, 7.84, 21.97, 70.19</td>
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<td>0.74, 18.51, 22.61, 58.88</td>
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<td>53.7</td>
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<td>0.98, 14.54, 19.92, 65.54</td>
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<td>90.4</td>
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<td>0.2</td>
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<td>87.4</td>
<td>12.2</td>
<td>0.4</td>
<td>0.0</td>
<td>0.45, 8.62, 13.07, 79.31</td>
</tr>
</tbody>
</table>

Notes: Rm = vitrinite reflectance under oil immersion. V = vitrinite; I = inertinite; E = exinite; M = minerals. Mad = moisture (air-dried basis); Ad = ash (dry basis); Vd = volatile (dry, ash free basis); FCd = carbon (air-dried basis).
3. Results and discussions

3.1. Relaxation properties of bulk water

To analyze the properties of fluid in coals by NMR measurement, the first and indispensable step is to establish a model for quantity characterization of water based on the NMR data. Fig. 1 shows the results of NMR $T_2$ distributions for different masses bulk water. The NMR $T_2$ spectra exhibits a clear peak, with a long relaxation time at approximately 200–1000 ms. As shown in Fig. 2, it can be found that the NMR spectra amplitude shows an evident linear relationship with bulk water mass,

\[ M_{\text{water}} = 1.0852 \times 10^{-4} \phi \quad (R^2 = 0.9933) \]

where $M_{\text{water}}$ is the mass of distilled water with units of g, $A$ (dimensionless) means the amplitude of measured NMR $T_2$ spectra.

3.2. Relaxation properties of samples with fully saturated water and after centrifugal experiment

Fig. 3 shows the results of NMR $T_2$ distribution for the fully saturated coals and after centrifugal experiments. The $T_2$ distribution of coals at fully saturated conditions are shown as blue lines in Fig. 3, which exhibit an evident multimodal distribution. The first dominant peak occurs at approximately 0.01–8 ms, with a slow relaxation property, indicating the characteristics of smaller pores in coals. The second peak is found between 10 and 100 ms, that corresponds to the larger pores in coals. For most of samples (except for sample #7) existing a third peak, with a fast relaxation property at >100 ms. That illustrates the fractures are well developed in these coals. Based on the NMR amplitude of coal samples under fully saturated condition and equation (2), the total NMR porosity ($\phi_{\text{NMR}}$) were obtained. Taken the sample #1 as an example, the total $T_2$ amplitude under fully-saturated-condition is 11652 (p.u.) (Table 2), corresponding to 1.2645 g water saturated in coal pore system based on equation (2). The volume of the coal plug is 24.53 cm$^3$ (size of 2.5 diameter and 5.0 cm length), thus, the NMR porosity for sample #1 is 5.16% – water volume divided by sample volume. The calculated values of $\phi_{\text{NMR}}$ for all coals range from 3.13 to 12.24% (Table 2).

With the increasing centrifugal pressures, the first dominant peak shows a slight decreasing trend for most coals (except for the sample #4 and #14). It should be noticed that the first peak of sample #4 and #14 exhibits a slight increase trend after 0.62 MPa and 0.92 MPa centrifugal experiments. This may because of the complicated pore morphology and spontaneous imbibition within micro-pores. While for the second and third peak, there is an evident reduction for all coal samples, that is the result of some movable fluids in coal pore-fracture system are centrifuged by centrifugal treatments.

3.3. Single $T_2$ cutoffs model

Previous studies (Ge et al., 2015b; Xu et al., 2017) have found that there was a single $T_2$ cutoff value (denoted as $T_{2c}$) can be calculated by combining NMR and centrifugal experiments. Based on this calculated $T_{2c}$, the pore fluids of rocks are classified into movable fluid part ($T_2 > T_{2c}$), and irreducible fluid part ($T_2 < T_{2c}$). Here, we defined this pore fluid classification standard as single $T_2$ cutoffs model. In this section, we calculated the values of $T_{2c}$ for all coal samples and discussed the limitations of the single $T_2$ cutoffs model.

3.3.1. Determination of $T_{2c}$

To calculate the values of $T_{2c}$, the first step is to determine the optimal centrifugal pressure based on the NMR results of different pressures centrifugal experiment. Fig. 4 and Table 3 show the water pressures were recorded.

Fig. 1. NMR $T_2$ distributions of bulk water with different masses.

Fig. 2. Relationship between the total NMR $T_2$ amplitude and bulk water mass.
Fig. 3. The single $T_2$ cutoffs and dual $T_2$ cutoffs determination by the NMR centrifugal experiments (to be continued).
Fig. 3. (continued).
saturations after centrifugal experiments for the studied plugs. As the centrifugal pressure increased from 0.69 MPa to 1.38 MPa, the water saturation results exhibit an evident downward trend. The relative error of water saturation after 1.15 MPa and 1.38 MPa centrifugal experiments for all coals in the range of 1.48–9.51%, averaging at ~5.0%. While the water saturation relative errors between 1.38 MPa and 1.61 MPa centrifugal pressures are less than 1.0%. We assumed the optimal numerical relative error index for determination optimal centrifugal pressure is 1.0%. Thus, the optimal centrifugal pressure to determinate T2C in this study is 1.38 MPa.

As shown in Fig. 5, in order to convenient and clearly calculate the T2C values, we only selected fully saturated and 1.38 MPa centrifugal NMR T2 distributions in Fig. 3. The method for determination T2C by centrifugal experiments were detailed in Yao et al. (2010). First, the two NMR T2 distributions under fully water-saturated condition and those after 1.38 MPa centrifugal experiments are transformed into two accumulative T2 curves (blue and red dotted line), respectively. Then, the horizontal line from the 1.38 MPa centrifugation cumulative T2 curve is drawn and intersects with fully water-saturated cumulative T2 curve at one point. Finally, the vertical line from this intersection point is drawn, intersecting with the X-axis which corresponds to the value of T2C. In this study, the calculated T2C in the range of 0.62–12.66 ms for all selected coals (Table 2), which shows a wider deviation than the values of shales (0.45–2.98 ms) calculated in Liu et al. (2018b).

Table 2
NMR single T2 cutoffs, dual T2 cutoffs, fully-saturated coal amplitude and porosity of coal samples.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Fully-saturated coal amplitude (p.u.)</th>
<th>ϕNMR (%)</th>
<th>Single T2 cutoffs model</th>
<th>Dual T2 cutoffs model</th>
<th>ϕ1 (%)</th>
<th>ϕ2 (%)</th>
<th>ϕ3 (%)</th>
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<td>#1</td>
<td>11652</td>
<td>5.15</td>
<td>2.43</td>
<td>0.85</td>
<td>4.30</td>
<td>0.16</td>
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<tr>
<td>#2</td>
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<td>3.16</td>
<td>3.35</td>
<td>0.10</td>
<td>0.76</td>
</tr>
<tr>
<td>#3</td>
<td>16043</td>
<td>7.10</td>
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<td>5.23</td>
<td>7.01</td>
<td>0.10</td>
<td>0.76</td>
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<tr>
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<td>4.16</td>
<td>0.10</td>
<td>0.76</td>
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<td>3.19</td>
<td>0.10</td>
<td>0.76</td>
</tr>
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<td>0.74</td>
<td>3.58</td>
<td>0.10</td>
<td>0.76</td>
</tr>
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</table>

Notes: ϕ1, ϕ2 and ϕ3 is absolute irreducible porosity, partial movable porosity and absolute movable porosity, respectively.

3.3.2. Limitation in the application of single T2 cutoffs model

One of the most important application of T2C is to distinguish the movable fluid and irreducible fluid. Conventionally, based on the values of T2C, the NMR T2 spectrum of a sample with fully saturated condition experiments for all coals in the range of 1.48–9.51%, averaging at ~5.0%. While the water saturation relative errors between 1.38 MPa and 1.61 MPa centrifugal pressures are less than 1.0%. We assumed the optimal numerical relative error index for determination optimal centrifugal pressure is 1.0%. Thus, the optimal centrifugal pressure to determinate T2C in this study is 1.38 MPa.

As shown in Fig. 5, in order to convenient and clearly calculate the T2C values, we only selected fully saturated and 1.38 MPa centrifugal NMR T2 distributions in Fig. 3. The method for determination T2C by centrifugal experiments were detailed in Yao et al. (2010). First, the two NMR T2 distributions under fully water-saturated condition and those after 1.38 MPa centrifugal experiments are transformed into two accumulative T2 curves (blue and red dotted line), respectively. Then, the horizontal line from the 1.38 MPa centrifugation cumulative T2 curve is drawn and intersects with fully water-saturated cumulative T2 curve at one point. Finally, the vertical line from this intersection point is drawn, intersecting with the X-axis which corresponds to the value of T2C. In this study, the calculated T2C in the range of 0.62–12.66 ms for all selected coals (Table 2), which shows a wider deviation than the values of shales (0.45–2.98 ms) calculated in Liu et al. (2018b).
can be divided into two parts: the $T_2 < T_{2C}$ for the irreducible fluid, and the $T_2 > T_{2C}$ for the movable fluid. In this study, when we tried to divide the coal reservoir fluid into irreducible fluid and movable fluid based on the $T_{2C}$, we found that it has some shortcomings in accurate quantitative characterization of different type pore fluids in coals.

Here, the coal sample #1 was taken as an example to illustrate the limitation of the single $T_2$ cutoffs model in typing movable and irreducible fluid. As shown in Fig. 5, it is easily to find that when $T_2 > T_{2C}$, there is still some irreducible fluid after high pressure centrifugal experiments (gray region in Fig. 5). It may be the result of there are still some irreducible fluid after high pressure centrifugal experiments, and we defined the transverse relaxation time boundary between the absolute movable fluid and partial movable fluid (denoted as $\phi_1$), partial movable porosity (denoted as $\phi_1$), and absolute movable porosity (denoted as $\phi_3$), respectively. The values of the $\phi_1, \phi_2$ and $\phi_3$ can be calculated as follows:

$$\phi_1 = \frac{\int_{T_{2C}}^{T_{\infty}} T_2 dT}{\int_{T_{\min}}^{T_{\max}} T_2 dT} \times \phi_{NMR}$$

$$\phi_2 = \frac{\int_{T_{\min}}^{T_{2C}} T_2 dT}{\int_{T_{\min}}^{T_{\max}} T_2 dT} \times \phi_{NMR}$$

$$\phi_3 = \frac{\int_{T_2}^{T_{\max}} T_2 dT}{\int_{T_{\min}}^{T_{\max}} T_2 dT} \times \phi_{NMR}$$

where $A_{\text{Fully}, T_2}$ and $A_{\text{Centrifugal}, T_2}$ is the NMR amplitude under fully water-saturated, after centrifugal condition at $T_2$, respectively. The minimum of $T_2$ that meets the conditions of Eq. (3) corresponding to $T_{2C1}$.

For the absolute movable fluid (green region in Fig. 6), the NMR $T_2$ distributions of the fluids complete disappeared after centrifugal experiments, and we defined the transverse relaxation time boundary between the absolute movable fluid and partial movable fluid as the $T_{2C2}$. For the partial movable fluid (blue region in Fig. 6), we can find that the $T_2$ distributions of $T_{2C1} < T_2 < T_{2C2}$ show an evident reduction after centrifugal experiments rather than complete remove, and we defined as this part of fluid as the partial movable fluids.

### 3.4. Dual $T_2$ cutoffs model

As discussed, the single $T_2$ cutoffs model cannot be accurately used to distinguish the different types of fluids in coals. In this section, a new model was introduced to accurate quantitative characterization of different pore fluids in coals determined from the perspective of NMR and centrifugal testing, that is dual $T_2$ cutoffs model.

#### 3.4.1. The principle of dual $T_2$ cutoffs model

As shown in Fig. 6, the coal sample #1 was taken as an example to illustrate the dual $T_2$ cutoffs model. These pore fluids in coals were reclassified into three types (absolute irreducible fluid, absolute movable fluid and partial movable fluid) rather than two commonly types (irreducible and movable fluid). For the absolute irreducible fluid (gray region in Fig. 6), the NMR $T_2$ spectra show almost no changes between the fully water-saturated and those after centrifugal experiments, which indicates the behavior of this part fluids are absolute irreducible. The transverse relaxation time boundary between the absolute irreducible fluid and partial movable fluid was denoted as $T_{2C1}$. It should be noticed that the NMR $T_2$ spectra of fully water-saturated and those may not extremely coincide in absolute irreducible fluid part for some samples. Here, the principle of $T_{2C1}$ determination was expressed as following:

$$\frac{A_{\text{Fully}, T_2} - A_{\text{Centrifugal}, T_2}}{A_{\text{Fully}, T_2}} > 0.01$$

where $A_{\text{Fully}, T_2}$ and $A_{\text{Centrifugal}, T_2}$ is the NMR amplitude under fully water-saturated, after centrifugal condition at $T_2$, respectively. The minimum of $T_2$ that meets the conditions of Eq. (3) corresponding to $T_{2C1}$.

For the absolute movable fluid (green region in Fig. 6), the NMR $T_2$ distributions of the fluids complete disappeared after centrifugal experiments, and we defined the transverse relaxation time boundary between the absolute movable fluid and partial movable fluid as the $T_{2C2}$. For the partial movable fluid (blue region in Fig. 6), we can find that the $T_2$ distributions of $T_{2C1} < T_2 < T_{2C2}$ show an evident reduction after centrifugal experiments rather than complete remove, and we defined as this part of fluid as the partial movable fluids.

### 3.4.2. Determination of $T_{2C1}$ and $T_{2C2}$

According to the above principle of dual $T_2$ cutoffs model, we calculated the $T_{2C1}$ and $T_{2C2}$ for all selected coal samples (see results in Fig. 3 and Table 2). In this study, the values of $T_{2C1}$ ranges from 0.10 to 0.34 ms, while the $T_{2C2}$ has a wider range from 1.05 ms to 439.76 ms.

Based on the calculated $T_{2C1}$ and $T_{2C2}$, a fully saturated NMR $T_2$ spectra of sample can be divided into three parts: $T_2 < T_{2C1}$ for the absolute irreducible fluid parts, $T_{2C1} < T_2 < T_{2C2}$ for the partial movable fluid parts and $T_{2C2} < T_2$ for the absolute movable fluid parts. Moreover, the NMR total porosity ($\phi_{NMR}$) of a coal sample can also be divided into three parts corresponds to the three types of pore fluids, which is absolute irreducible porosity (denoted as $\phi_1$), partial movable porosity (denoted as $\phi_1$), and absolute movable porosity (denoted as $\phi_3$), respectively. The values of the $\phi_1, \phi_2$ and $\phi_3$ can be calculated as follows:

$$\phi_1 = \frac{\int_{T_{2C1}}^{T_{\infty}} T_2 dT}{\int_{T_{\min}}^{T_{\max}} T_2 dT} \times \phi_{NMR}$$

$$\phi_2 = \frac{\int_{T_{\min}}^{T_{2C1}} T_2 dT}{\int_{T_{\min}}^{T_{\max}} T_2 dT} \times \phi_{NMR}$$

$$\phi_3 = \frac{\int_{T_{2C2}}^{T_{\max}} T_2 dT}{\int_{T_{\min}}^{T_{\max}} T_2 dT} \times \phi_{NMR}$$

where $T_{\min}$ is 0.01 ms; $T_{\max}$ is 10000 ms; $T_{2C1}$ is the $T_2$ cutoff between absolute irreducible and partial movable fluids, and $T_{2C2}$ is the $T_2$ cutoff between partial movable and absolute movable fluid; $\phi_{NMR}$ is the total porosity measured by NMR experiments.

The calculated $\phi_1$, $\phi_2$ and $\phi_3$ for all selected coals are shown in Table 2. Values of $\phi_1, \phi_2$ and $\phi_3$ are in the range of 0.16–1.49% (average at 0.65%), 1.85–10.87% (average at 4.98%), and 0.01–1.28% (average at 0.40%), respectively. Of the three porosities, $\phi_3$ accounts for largest proportion of the total porosity, secondly is $\phi_1$, and $\phi_3$ contributes the lowest proportion.

### 3.5. NMR full-scale PSD

The NMR spectra with fully saturated conditions only can provide $T_2$ distributions rather than the absolute full-scale PSD. There are two commonly used methods to acquire the full-scale PSD based on NMR measurement. One is centrifugal experiment method, the other is surface relaxivity method.

For the centrifugal experiment method, three steps should be performed to acquire the full-scale PSD that can be found in Yao et al. (2010). The first step is to determine an optimal centrifugal pressure and the values of $T_{2C}$ by a series of centrifugal experiments. Then, the second step is to calculate the pore radius ($r$) corresponding to the determined optimal centrifugal pressure based on Washburn equation. At last, the full-scale PSD is determined based on the relationship of any transverse relaxation time ($T_2$) and pore radius ($r$) that is the $r = \frac{2T_2}{\pi}$ It should be noticed that the determined $T_{2C}$ is not an accurate and absolute value, since there are still some movable fluids when $T_2 < T_{2C}$. Thus, the...
full-scale PSD determined by the centrifugal experiment method is inapplicable.

For the surface relaxivity method, Zheng et al. (2019) proposed a novel method for calculation surface relaxivity of coals by combining low-temperature nitrogen adsorption (LTNA) and mercury intrusion porosimetry (MIP), and provided the references of surface relaxivity for different coals. They suggested 2.1 μm/s, 3.0 μm/s and 1.6 μm/s for the surface relaxivity of low-, medium-, and high-rank coal. According to the
references of surface relaxivity in Zheng et al. (2019), the full-scale PSD in this study were obtained (Fig. 7).

As shown in Fig. 7, based on the dual $T_2$ cutoffs model, the PSD of coals were reclassified into three types: absolute irreducible fluid pores ($r < r_1$), partial movable fluid pores ($r_1 < r < r_2$) and absolute movable fluid pores ($r_2 < r$). Noted that $r_1$ is the threshold pore radius of absolute irreducible fluid pores corresponding to $T_{2C1}$, $r_2$ is the threshold pore radius of absolute movable fluid pores corresponding to $T_{2C2}$. As shown
in Fig. 7, \( r_1 \) commonly have very low values in the range of 0.42–2.07 nm, while \( r_2 \) ranges from 6.28 nm to 1846.99 nm.

Taking the sample #1 as example, the full-scale PSD classification petrological model that derived from the dual \( T_2 \) cutoffs model was elucidated (Fig. 8). As shown in Fig. 8, the absolute irreducible fluid pores, partial movable fluid pores, and absolute movable fluid pores are in the radius of <0.67 nm, 0.67 nm–144.48 nm, and >144.48 nm, respectively. The absolute irreducible fluid pores are commonly developed in coal matrix and contribute little to fluid transportation, and the partial movable fluid pores mainly developed in mesopores, such as gas pores and tissue pores. The absolute movable fluid pores are usually related to fractures, that is good for pore fluid migration.

4. Conclusions

This paper presented a significant model for pore fluid type and PSD classification in coals by combining NMR and centrifugal experiments. The main conclusions are as follows:

(1) Based on NMR and centrifugal experiments, the \( T_{2C} \) of coals determined by the single \( T_2 \) cutoff model in the range of 0.62–12.66 ms. When \( T_2 > T_{2C} \), there is remaining some irreducible fluid in pores. There are still some movable fluids in pores when \( T_2 < T_{2C} \), which indicates the single NMR \( T_2 \) cutoffs model has some obvious shortcomings in pore fluid classification.

(2) An effective method was proposed for pore fluid typing classification of coals denoted as the dual \( T_2 \) cutoffs model. For a typical \( T_2 \) spectrum with fully-saturated condition, the pore fluid of coals was re-classified into absolute movable fluid (\( T_2 > T_{2C_2} \)), partial movable fluid (\( T_{2C_1} < T_2 < T_{2C_2} \)), and absolute irreducible fluid (\( T_{2C_1} > T_2 \)). For all coal samples, the \( T_{2C_1} \) ranges from 0.10 to 1.32 ms, while \( T_{2C_2} \) in the range of 36.12–89.07 ms.

(3) Based on dual \( T_2 \) cutoffs model, a conceptional model were proposed to clarify a full-scale PSD classification: absolute irreducible fluid pores, partial movable fluid pores and absolute movable fluid pores.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationshipsthat could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Sijian Zheng: Validation, Writing - original draft, Investigation.
Yanbin Yao: Conceptualization, Methodology, Supervision, Project administration, Funding acquisition. Derek Elsworth: Writing - review & editing. Bo Wang: Resources. Yong Liu: Formal analysis.

Acknowledgments

We acknowledge financial support from the National Natural Science Foundation of China (41830427; 41872123), the National Major Science and Technology Projects of China (2016ZX05043-001), the Key research and development project of Xinjiang Uygur Autonomous Region (2017B03019-1), and the Fundamental Research Funds for the Central Universities (292019252).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jngse.2020.103466.