A method to determine nuclear magnetic resonance $T_2$ cutoff value of tight sandstone reservoir based on multifractal analysis

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Abstract
Nuclear magnetic resonance (NMR) $T_2$ cutoff value is an important parameter for pore structure evaluation. It is complicated and uneconomical to obtain $T_2$ cutoff value by an experimental method; therefore, it is necessary to explore a prediction method of $T_2$ cutoff value. In this paper, 10 samples of tight gas reservoirs in the eastern Ordos Basin were selected, and then saturation and centrifugal experiments of nuclear magnetic resonance were carried out. On this basis, multifractal theory was introduced to calculate the multifractal characteristics of the NMR $T_2$ spectrum of each sample, and the relationship between multifractal parameters and $T_2$ value was analyzed. The influencing factors of the $T_2$ cutoff value were clarified, and the prediction model of the $T_2$ cutoff value was constructed accordingly. The results show that the $T_2$ spectra of sandstones in the study area can be divided into three types: single steeple peak, double steeple peak, and irregular double peak. The pore diameter of the three types is 1 nm ~ 3×10^4 nm, 1 nm ~ 10^4 nm and 1 nm ~ 4×10^3 nm, respectively. The $T_2$ cutoff value ranges from 9.72 to 35.16 ms. The correlation analysis suggests that the symmetrical fractal dimension difference and symmetrical multifractal dimension ratio ($D_{\text{min}} - D_{\text{max}}$, $D_{\text{min}} / D_{\text{max}}$) shows a positive linear correlation with the $T_2$ cutoff value. The value of $T_2$ cutoff gradually decreases with the increase of the flow zone indicator ($FZI$). Therefore, three parameters, including symmetrical fractal dimension difference, symmetrical multifractal number ratio, and $FZI$ are optimized, and the prediction model for the NMR $T_2$ cutoff value of sandstone samples in the study area is proposed. The introduction of porosity-related parameters compensates for the shortcomings of previous $T_2$ cutoff value prediction models. At the same time, the prediction model is proven to be accurate and reliable by testing the measured data of the samples near the study area. The results of this paper can be used for further study of the NMR $T_2$ cutoff value prediction of tight sandstone reservoirs in different areas.

KEYWORDS
Multifractal, Ordos basin, Pore size distribution, Sandstone reservoir, $T_2$ cutoff value, Tight gas
1 | INTRODUCTION

Large numbers of micron-nanometer pores, developed in tight sandstone reservoirs, can provide reservoir space for oil and gas accumulation. However, oil and gas show poor seepage ability since the pore throat diameter is generally a few nanometers and the pore structure is complex, difficult phase differentiation is therefore easy to be retained and adsorbed. Therefore, it is of great theoretical and practical significance to carry out micro-nano pore evaluation of tight reservoirs. In recent decades, the main experiments that can be used to quantitatively determine pore structure are capillary pressure curve method, binary image computer analysis (PIA), displacement method, and the pore three-dimensional space shape computer reconstruction method.\(^1\)\(^\text{-}^\text{11}\) As classical high-precision experiments for pore structure analysis, mercury intrusion analysis has been widely used. However, it has many defects, such as core damage, environmental pollution and high cost, so it is difficult to carry out on a large scale. The emergence of nondestructive NMR core analysis technology provides a new technology for the rapid and quantitative evaluation of reservoir pore structures. It has been widely used in pore structure characterization of coal, shale, sandstone, and other porous rocks. For NMR technology, the capillary pressure information can be obtained from the NMR \(T_2\) spectrum, which can be used for pore structure evaluation. Therefore, it has been a hot spot in pore evaluation.\(^12\)\(^\text{-}^\text{17}\)

The NMR \(T_2\) contains a lot of information related to the fluid in porous media, including pore size distribution (PSD), and pore connectivity,\(^18\)\(^\text{-}^\text{19}\) and can be used for pore structure evaluation, pore type characterization, capillary pressure reconstruction, calculation of porosity, and movable fluid saturation.\(^20\) It is an important parameter for evaluating the reservoir properties of sandstone, shale, and coal.\(^21\)\(^\text{-}^\text{23}\) Previous studies considered that the \(T_2\) cutoff value of the same lithology sample is fixed based on the literature review; for example, the default \(T_2\) cutoff value of sandstone is 33 ms, while limestone \(T_2\) cutoff value is 100 ms.\(^24\)\(^\text{-}^\text{25}\) However, follow-up studies show that even for different samples of the same lithology, the \(T_2\) cutoff value often varies.\(^26\)\(^\text{-}^\text{27}\) For example, the \(T_2\) cutoff value of coal and shale ranges from 2.5 to 32 ms, and 0.45 to 2.98 ms, respectively.\(^13\)\(^\text{-}^\text{28}\) Therefore, it is not advisable to evaluate the physical characteristics of a sample with a fixed \(T_2\) cutoff value.

To evaluate reservoir physical properties accurately, it is particularly important to obtain accurate \(T_2\) cutoff values. Researchers have proposed many single factor prediction models for \(T_2\) cutoff values based on data statistics. The influencing parameters of \(T_2\) cutoff values are considered as temperature, composite indicator of pore structure, irreducible water saturation, formation pressure, cation exchange capacity, and magnetic susceptibility, respectively.\(^29\)\(^\text{-}^\text{34}\) However, factors affecting the \(T_2\) cutoff value are complex and diverse. The variation of a single factor may result in differences in the \(T_2\) cutoff value. Therefore, these single factor \(T_2\) cutoff value prediction models have some limitations and cannot be widely used.

In recent years, fractal theory has been applied to pore evaluation of porous media, including prediction of \(T_2\) cutoff value.\(^19\) Fractal analysis theory has been gradually adopted as a new method to study nonlinear complex systems and used to study pore structure in rocks.\(^35\)\(^\text{-}^\text{41}\) However, it has been found that there are limitations to describe the complex pore structure evolved from nonlinear evolution with only one fractal dimension. For example, the porosity of rocks with the same fractal dimension may vary differently.\(^42\)\(^\text{-}^\text{44}\) The multifractal theory was introduced with the deepening of research.\(^45\) Compared with single fractal, the multifractal theory can decompose the self-similarity measure into staggered fractal sets and decompose the complex fractal structure into several parts to characterize the local complexity and heterogeneity of pore distribution, so as to identify the micro-local characteristics of pore distribution.\(^39\)\(^\text{-}^\text{46}\)\(^\text{47}\)

Former researchers show that there is a close relationship between the PSD of rocks and multifractal parameters.\(^47\)\(^\text{54}\) In addition, some scholars have found that multifractal parameters (such as \(D_{\min}-D_{max}\) and \(D_{\min}/D_{max}\)) \(\Delta(\alpha)\) are closely related to the \(T_2\) cutoff value in coal and sandstone reservoirs.\(^47\)\(^\text{50}\)\(^\text{52}\)\(^\text{54}\) The corresponding prediction models of \(T_2\) cutoff value have been proposed based on the multifractal parameters. However, there are only multifractal parameters in the prediction model. As we all know, multifractal theory studies the geometric characteristics of objects (such as shape features of \(T_2\) spectrum), which are only related to the distribution of objects. The multifractal parameters of the NMR \(T_2\) spectra with the same shape and different locations on the X-axis are identical. However, the total pore size and single pore size of the reservoir represented by these two NMR \(T_2\) spectra are quite different. Under the conditions of completely equal pore connectivity, the permeability of the reservoir is obviously different, and the \(T_2\) cutoff value is also obviously different. Therefore, taking only multifractal parameters into account when establishing \(T_2\) cutoff value prediction model may lead to the inaccuracy of the prediction model. It is necessary to consider the parameters related to the location of \(T_2\) spectrum in the X-axis (such as porosity and \(T_{2_{\text{lim}}})\).

Therefore, based on the study of multifractal parameters (such as multifractal dimension, mass index, and singular strength) of 10 sandstone samples, this study analyzed the correlation between multifractal parameters and \(T_2\) cutoff value, the main parameters affecting \(T_2\) cutoff value was studied, and a new prediction equation for \(T_2\) cutoff value of sandstone
reservoir was proposed using the multifractal parameters and \textit{FZI}, which is closely related to the reservoir porosity.

2 | EXPERIMENTAL AND MULTIFRACTAL THEORY

2.1 | Sample information

Based on core observation and gas test data, a total of 10 representative sandstone samples from Benxi, Taiyuan and Shanxi Formations of Upper Paleozoic in eastern Ordos Basin, China, were selected. These samples were sampled from 9 coring wells (Figure 1) with burial depth of 2280 m – 3267 m and were prepared into cylinders with a diameter of 25 mm and a length of 35 mm. Physical properties of all the samples were analyzed first in the Key Laboratory of Coalbed Methane Resources and Reservoir Formation Process of the Ministry of Education of China University of Mining and Technology following the Chinese Oil and Gas Industry Standard GB/T 29172-2012. Then, the NMR analysis was carried out. The detail information of the samples is listed in Table 1.

2.2 | NMR centrifugal experiments

Nuclear magnetic resonance $T_2$ spectrum was tested in the Key Laboratory of Continental Dynamics, Northwestern University by using SPEC-PMR-2M low magnetic field nuclear magnetic resonance instrument with the main magnetic field 0.047T, the resonance frequency of hydrogen nucleus 2 MHz, the magnet controlled temperature 35°C, and the power of radio frequency 300 W. The experiment parameters were set up with a waiting time of 3000 ms, echo spacing of 0.3 ms, and echo numbers of 4096. The saturated fluid of samples is sodium chloride solution with 10% concentration. The experimental temperature and humidity are 25°C and 50%, respectively. Ten core columns with diameter of 25 mm and length of 50 mm are tested. The flowcharts of the NMR experiment are as follows:

1. Wash and dry the core sample, and weigh it;
2. Put the core plug into the ultralow permeability core vacuum saturation meter, vacuum under 1MPa for 24h, and pressurize the saturated standard brine under the pressure of 30MPa until the pressure in the saturated tank no longer drops, (standard salt water is formulated according to the formula NaCL : CaCL$_2$ : MgCL$_2$.6H$_2$O mass ratio 7.0 : 0.6 : 0.4);55;
3. Place the water saturated core in a test tube and placed in a nuclear magnetic resonance apparatus to test the $T_2$ spectrum under saturated water. The experimental method is based on the experimental measurement standard of rock sample nuclear magnetic resonance parameters,56 and the main test parameters are echo interval 0.3 ms, waiting time 3000 ms, acceptance gain 80%, and echo number 4096.
4. The saturated water sample was centrifuged on a high-speed centrifuge for 5 hours, and the fully centrifuged sample was subjected to nuclear magnetic resonance analysis according to the parameters of step 3.

2.3 | Analysis of multifractal theory

Mandelbrot first proposed the multifractal characteristics of complex systems in 1974.57 With the continuous development and promotion of many researchers, the multifractal theory has been applied to many fields such as geoscience and material science and has become an important new method for pore structure characterization.45,58-60 The predecessors elaborated the concrete connotation and algorithm of multifractal theory, and made a brief overview.51,61 The key of multifractal is to analyze the probability distribution of variables at different scales. In this paper, the box-counting method was used to investigate the multifractal characteristics of NMR $T_2$ spectrum which reflecting the heterogeneity of pore size distribution of selected sandstone samples.

Divide the study subject into $N$ equal size box ( \( N = 2^k, k = 1,2,3,… \) ), The scale of each box is $\varepsilon$, The probability mass function for the $i$th box with a scale $\varepsilon$ can be expressed as follows\textsuperscript{19}:

$$\varepsilon = 2^{-k}L$$

(1)

$$P_i(\varepsilon) = \frac{N_i(\varepsilon)}{\sum_{i=1}^{N(\varepsilon)} N_i(\varepsilon)}$$

(2)

where $N(\varepsilon)$ is the cumulative porosity or pore volume of partition $i$, and $P_i(\varepsilon)$ is the probability mass function and satisfy a power exponent relationship with the box scale $\varepsilon$, which can be expressed as\textsuperscript{60}:

$$P_i(\varepsilon) \propto \varepsilon^{-\alpha_i}$$

(3)

$\alpha_i$ is the singularity strength, characterizing the distribution density of the $i$th box for scale $\varepsilon$, and it is related to the region, reflecting the probability of the region.

Define the number of boxes with the same $\alpha$ value as $N_{\alpha}(\varepsilon)$, then:

$$N_{\alpha}(\varepsilon) \propto \varepsilon^{-f(\alpha)}, \varepsilon \rightarrow 0$$

(4)

In which, $f(\alpha)$ is the multifractal spectrum and represents the fractal dimension of a subset with the same
singularity index. Singularity index $\alpha$ and $f(\alpha)$ can be solved by CHHABRA and JENSEN methods.\textsuperscript{62} The expressions are as follows:

\[ \alpha(q) = \frac{\sum_{i=1}^{N} u_i(q,\epsilon) \log \epsilon}{\log \epsilon} \]

\[ f(\alpha) = \frac{\sum_{i=1}^{N} u_i(q,\epsilon) \log u_i(q,\epsilon)}{\log \epsilon} \]

In which:

\[ u_i(q,\epsilon) = \frac{p_i^q(\epsilon)}{\sum_{i=1}^{N} p_i^q(\epsilon)} \]

where $q$ is an order of the matrix, which can be ranged from $-\infty$ to $+\infty$. For multifractals, the denominator in Equation (7) is partition function, also known as statistical moment function, and its expression is as follows:

\[ X(q,\epsilon) = \sum_{i=1}^{N} p_i^q(\epsilon) \propto \epsilon^{\tau(q)} \]

where $\tau(q)$ is the mass exponent and can be expressed as follows:

\[ \tau(q) = -\lim_{\epsilon \to 0} \frac{\log \sum_{i=1}^{N} p_i^q(\epsilon)}{\log \epsilon} \]

$\alpha - f(\alpha)$ is a set of parameters describing the local characteristics of multifractal. The other set is $q \sim D(q)$, which is

\textbf{FIGURE 1} Geological settings of the study area. A, Structural distribution map of Ordos Basin, B, sampling well location distribution, and C, stratigraphic comprehensive columnar map of the study area

\textbf{TABLE 1} Basic information of selected sandstone samples

| Sample | Well | Formation | Depth (m) | $\Phi$ Helium (%) | $\Phi$ Water (%) | $K$ Helium (mD) |
|--------|------|-----------|-----------|-------------------|-----------------|-----------------|
| #1     | fu4  | Shan1     | 2305.10   | 12.6              | 11.87           | 1.77            |
| #2     | shuang3 | Shan2    | 2778.32   | 9.8               | 8.68            | 0.46            |
| #3     | yu86 | Shan2     | 2617.68   | 7.93              | 7.29            | 1.23            |
| #4     | shuang95 | Taiyuan | 2471.93   | 7.9               | 7.25            | 0.33            |
| #5     | shuang3 | Taiyuan | 2824.76   | 11.36             | 11.03           | 1.09            |
| #6     | tong12 | Benxi    | 2979.28   | 8.3               | 7.54            | 2.55            |
| #7     | shan394 | Shan1    | 2898.85   | 5.61              | 5.24            | 0.39            |
| #8     | mi9  | Shan2     | 2652.08   | 10.9              | 10.41           | 0.48            |
| #9     | zhenchuan8 | Taiyuan | 2280.03   | 8.73              | 8.21            | 1.73            |
| #10    | shan247 | Benxi    | 3266.11   | 9                 | 8.6             | 1.01            |
introduced from the perspective of information theory. The formula of \( D(q) \) can be expressed as\(^{54} \):

\[
D(q) = \frac{1}{q-1} \lim_{\varepsilon \to 0} \frac{1}{\log \varepsilon} \sum_{i=1}^{N(\varepsilon)} p_i^{\text{f}}(\varepsilon) \log p_i^{\text{f}}(\varepsilon) = \tau(q) \quad (10)
\]

The relationship between the generalized fractal dimension and the multifractal spectrum satisfies the Legendre relationship,\(^{62} \) and its expression is as follows:

\[
a(q) = \frac{dq}{dq} (11)
\]

\[
f(a) = q \times a(q) - \tau(q) \quad (12)
\]

According to the above formulas, the parameters of \( D(q) \), \( a(q) \), \( f(a) \), and \( \triangle a \) are calculated based on the procedure written in MATLAB (version 2018) to characterize the multifractal characteristics of sandstone NMR \( T_2 \) spectrum.

### 3 | RESULTS AND DISCUSSIONS

#### 3.1 | Characteristics of the sandstone samples

The 10 samples were selected are mainly quartz without feldspar. The water measured porosity of sandstone samples ranged from 5.24% to 11.87%, with an average of 8.61%, the gas measured porosity ranged from 5.61% to 12.6%, with an average of 9.21%, and the NMR tested porosity ranged from 5.26% to 12.16%, with an average of 8.81% (Table 2). The correlation between water porosity, gas porosity, and NMR porosity is obvious (Figure 2). The water porosity is slightly smaller than that of NMR, and the gas porosity is slightly larger than that of the NMR. The relative error between the two porosity and NMR porosity is less than 6.66%.

#### 3.2 | \( T_2 \) Spectrum distribution characteristics of sandstone samples

The pore structure of the reservoir controls the distribution of pore fluid. The distribution characteristics of NMRT\( _2 \) spectrum can indirectly reflect the pore size distribution and fluid distribution. NMR analysis of 100% standard brine saturated and fully centrifuged tight reservoir samples has been carried out to determine the movable and immovable fluid saturation of the tight reservoir samples (Figure 3 and Table 2). The NMRT\( _2 \) spectrum can be divided into three types: single steeple peak type (type 1, samples 2, 3, 6), double steeple peak type (type 2, samples 4, 5, 9, and irregular double peak type (type 3, samples 1, 7, 8, 10) based on the shape characteristics. From type 1 to type 3, pore size distribution varies from concentration to dispersion, movable fluid saturation decreases from 87.94% to 34.23% gradually and bound water saturation increases from 31.8% to 65.77%. It indicate that the pore size and structure are becoming more complex and the physical properties get worse, which can be proved by the diffusion effect of the irregular bimodal.

#### 3.3 | The application of NMR \( T_2 \)

The water saturated \( T_2 \) distribution corresponds to the pore structure of samples, which can well reflect the pore size distribution of capillary and the pore space containing fluid in the reservoir. In terms of relaxation time (\( T_2 \)), the quantitative parameters reflecting pore size distribution and proportions and controlling fluid movement characteristics mainly include \( T_2 \), \( T_2 \) cutoff value and so on. The \( T_2 \) is proportional to pore throat radius \( r_c \)\(^{63} \) (Equation 13), where the \( C \) is the conversion coefficient between \( T_2 \) and \( r_c \), and the value of \( C \) can be calculated with the parameters porosity and permeability with Equation 14.\(^{64} \) the values of \( C \) for selected samples are listed in Table 2. The pore diameter distribution of three types of sandstone samples is shown in Figure 4A,B and C.

| Samples | \( \Phi_{\text{NMR}} \) (%) | \( K_{\text{Helium}} \) (mD) | \( T_2 \) cutoff value (ms) | Movable water saturation (%) | Irreducible water saturation (%) | \( \Phi_{\text{effective}} \) (%) | \( C \) |
|---------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----|
| #1      | 12.16           | 1.77            | 17.71           | 42.31           | 57.69           | 5.15            | 100.7 |
| #2      | 8.98            | 0.46            | 35.16           | 68.19           | 31.81           | 6.13            | 47.7  |
| #3      | 7.74            | 1.23            | 24.29           | 87.94           | 12.06           | 6.81            | 63.6  |
| #4      | 7.4             | 0.33            | 27.47           | 50.49           | 49.51           | 3.73            | 41.3  |
| #5      | 11.1            | 1.09            | 24.70           | 61.65           | 38.35           | 6.84            | 71.3  |
| #6      | 7.66            | 2.55            | 9.72            | 87.66           | 12.34           | 6.72            | 97.3  |
| #7      | 5.26            | 0.39            | 10.78           | 36.05           | 63.95           | 1.90            | 39.7  |
| #8      | 10.62           | 0.48            | 29.5            | 34.29           | 65.71           | 3.64            | 50.0  |
| #9      | 8.42            | 1.73            | 10.7            | 61.30           | 38.70           | 5.16            | 79.2  |
| #10     | 8.77            | 1.01            | 20.54           | 34.23           | 65.77           | 2.66            | 61.7  |
sulting in a significant decrease in seepage capacity of pore. That with the decrease of pore radius, pore structure and pore water saturation increases significantly. The main reason is porosity decrease gradually, while the average irreducible average movable fluid saturation and the movable fluid an average of 3.837%. From the type 1 to the type 3 samples, irreducible water porosity ranges from 0.93% to 7.01%, with 1.9% to 6.84%, with an average of 4.874%, while the range of saturation ranges from 12.06% to 65.71%, with an average 87.94%, with an average of 56.41%, and the irreducible water Table 2. The movable fluid saturation ranges from 34.23% to calculated based on the experimental results, as is shown in NMR experiments. According to the $T_2$ cutoff value is an important parameter related to pore fluid movement characteristics and pore throat based on NMR experiments. According to the $T_2$ cutoff value, the fluid in pore can be divided into movable fluid and irreducible water saturation, corresponding to movable fluid porosity and bound water porosity respectively. The movable fluid saturation and irreducible water saturation of sandstone samples are calculated based on the experimental results, as is shown in Table 2. The movable fluid saturation ranges from 34.23% to 87.94%, with an average of 56.41%, and the irreducible water saturation ranges from 12.06% to 65.71%, with an average of 43.59%. The range of movable fluid porosity ranges from 1.9% to 6.84%, with an average of 4.874%, while the range of irreducible water porosity ranges from 0.93% to 7.01%, with an average of 3.837%. From the type 1 to the type 3 samples, the average movable fluid saturation and the movable fluid porosity decrease gradually, while the average irreducible water saturation increases significantly. The main reason is that with the decrease of pore radius, pore structure and pore connectivity tends to be complex and worse, respectively. Then, the resistance of fluid displacement increases and resulting in a significant decrease in seepage capacity of pore.

3.4 | Multifractal characteristics based on NMR experiments

The $T_2$ distribution of saturated sandstone samples is analyzed by multifractal theory. The results show that there is a good linear relationship between $\log X(q, e)$ and $\log (e)$ (Figure 5), which indicates that the pore size distribution of sandstone samples conforms to multifractal characteristics. Taking the $q$ range $[-10, 10]$, with the spacing of 0.1, $D_{-10}$ and $D_{10}$ represent $D_{min}$ and $D_{max}$ respectively, calculating the multifractal parameters of each sample based on Equation , and. The result is shown in Table 3. In which, $D_0$ is a capacity dimension. The value of $D_0$ has nothing to do with the number of voids in each box. It is only related to whether or not the voids are included and cannot be used to reflect the distribution characteristics of the voids. $D_1$ is an information entropy dimension, which is related to the entropy value of the system. It can be used to characterize the heterogeneity of pore distribution. The higher the $D_1$ value, the wider the pore distribution range and the stronger the heterogeneity. $\triangle D = D_{min} - D_{max}$ is the bending degree of the generalized dimension curve. The value of $\triangle D$ reflects the variation degree of local pore characteristics. The larger the value of $\triangle D$, the stronger the variation degree of pore. $D_0, D_1$ can also be used to characterize the pore characteristics of samples, reflecting the dispersion degree of pore distribution. The smaller the $D_0, D_1$ value, the more uniform the pore distribution in the dense area, the smaller the dispersion degree.

The generalized pore dimension spectra of sandstone samples are shown in Figure 6. Within the range of $[-10, 10]$, with the increase of $q$ value, the curve decreases monotonously, which indicates that the pore structure of sandstone samples satisfies the multifractal characteristics. When $q < 0$, $D_q$ decreases rapidly with the increase of the value of $q$, while when $q > 0$, $D_q$ decreases slowly with the increase of $q$ value. The greater the degree of curve bending, the stronger the heterogeneity of pore distribution.

Figure 7 shows that the relationship between $\tau(q)$ and $q$. $\tau(q)$ increases strictly with the increase of $q$ value, showing a convex feature. When $q < 0$, $\tau(q)$ increases significantly with the increase of $q$ value, while when $q > 0$, $\tau(q)$ increases slowly with the increase of $q$ value.

The multifractal singular spectral function $\alpha-f(\alpha)$ of pore distribution presents a continuous convex curve, and each group of curves shows a certain degree of asymmetry as is shown in Figure 8. $\triangle \alpha$ is the width of multifractal spectrum, and the value of $\triangle \alpha$ ranges from 2.382 to 3.316, with an average of 2.92. The larger the $\triangle \alpha$ is, the more complex the pore distribution is, corresponding the higher degree of inhomogeneity.

3.5 | T2 Analysis of influence parameters of $T_2$ cutoff value

3.5.1 | Relationships between $T_2$ cutoff value and multifractal parameters

The $T_2$ cutoff value and multifractal parameters are closely related to pore structure and size distribution of rock samples.
FIGURE 3  The NMR $T_2$ spectra of selected tight sandstone samples. A, The pore size distribution of type 1 samples. B, Pore size distribution of type 2 samples. C, The pore size distribution of type 3 samples.
Therefore, it is significant to investigate the relationship between $T_2C$ and multifractal parameters, which predicting the value of $T_2C$. Figure 9 shows the relationship between $T_2$ cutoff value and multifractal dimension $D_q$ under different $q$ values. When $q < 0$, the NMR $T_2$ cutoff value is positively correlated with $D_q$, and when $q < 0$, the correlation coefficient decreases significantly as $q$ approaches 0. When $q = 0$, $D_q$ is almost unchanged. $D_{-q}D_q$ and $D_{-q}/D_q$ are represents symmetrical multifractal dimension difference and symmetrical multifractal dimension ratio, respectively. Compared with $D_q$, $D_{-q}D_q$ and $D_{-q}/D_q$ are better correlated with $T_2$ cutoff value, and the correlation coefficient increases gradually with the increase of $q$ absolute value (Figures 10 and 11). Figure 12 shows that there is no significant correlation between $T_2$ cutoff value and multifractal parameter $\Delta \alpha$. Therefore, $D_{min}$-$D_{max}$ and $D_{max}/D_{min}$, with the largest correlation coefficient with the NMR $T_2$ cutoff value, are selected to predict NMR $T_2$ cutoff value of sandstone samples.

3.5.2 Relationships between $T_2$ cutoff value and $FZI$

The complex pore structure and pore size distribution of tight sandstone control the variation of permeability...
parameters. Kazni proposed a new parameter to characterize the pore throat ratio of reservoir, that is, flow zone index (FZI). The larger the FZI value, the better the pore throat matching relationship of reservoir. That is, FZI is also a parameter reflecting the quality of pore structure.68

\[
FZI = \left[ \frac{1 - \frac{\varphi}{\varphi}}{\sqrt{K/\varphi}} \right] \times \sqrt{K/\varphi}
\]  

(15)

Since FZI and the NMR $T_2$ cutoff value are both controlled by reservoir pore structure, which are important parameters to

| Samples | $D_{\min}$ | $D_{-2}$ | $D_{-1}$ | $D_0$ | $D_1$ | $D_2$ | $D_{\max}$ | $D_{\min} - D_{\max}$ | $D_{\min}/D_{\max}$ | $-\alpha$ |
|---------|------------|----------|----------|-------|-------|-------|------------|------------------------|------------------------|---------|
| #1      | 3.29       | 2.32     | 1.66     | 0.92  | 0.86  | 0.84  | 0.76       | 2.53                   | 4.33                   | 3.316   |
| #2      | 3.50       | 2.57     | 1.93     | 0.92  | 0.81  | 0.78  | 0.71       | 2.79                   | 4.93                   | 3.156   |
| #3      | 3.22       | 2.49     | 2.00     | 0.93  | 0.75  | 0.70  | 0.63       | 2.59                   | 5.11                   | 2.441   |
| #4      | 3.54       | 2.58     | 1.92     | 0.92  | 0.85  | 0.83  | 0.78       | 2.76                   | 4.54                   | 3.143   |
| #5      | 3.62       | 2.64     | 1.97     | 0.92  | 0.83  | 0.80  | 0.74       | 2.88                   | 4.89                   | 3.266   |
| #6      | 2.77       | 2.03     | 1.55     | 0.91  | 0.79  | 0.75  | 0.75       | 2.02                   | 3.69                   | 2.382   |
| #7      | 3.11       | 2.34     | 1.76     | 0.93  | 0.84  | 0.81  | 0.78       | 2.33                   | 3.99                   | 2.763   |
| #8      | 3.42       | 2.55     | 1.98     | 0.92  | 0.78  | 0.76  | 0.70       | 2.72                   | 4.89                   | 2.821   |
| #9      | 3.20       | 2.23     | 1.58     | 0.93  | 0.83  | 0.82  | 0.77       | 2.43                   | 4.16                   | 3.249   |
| #10     | 3.08       | 2.25     | 1.69     | 0.91  | 0.84  | 0.82  | 0.77       | 2.31                   | 4.00                   | 2.656   |
measure reservoir mobility, there must be some relationship between them. Comparing the FZI values of all sandstone samples with the T2 cutoff value, it is found that the FZI values are positively correlated with the saturation of movable fluids (Figure 13) and negatively correlated with the T2 cutoff value (Figure 14). Therefore, FZI values can also be used as an important parameter for predicting the NMR T2 cutoff value.

4 | PREDICTION MODEL FOR T2 CUTTOFF VALUE CALCULATION

Through the above analysis, it can be seen that there is significant correlation between T2 cutoff value and multifractal parameters as well as porosity and permeability parameters FZI. It is necessary to propose a mathematical equation for calculating the NMR T2 cutoff value. Therefore, Dmin/Dmax and Dmin/Dmax combined with FZI, are selected for predicting the T2 cutoff value of sandstone samples, the mathematical formulas for predicting T2 cutoff value are obtained by multiple linear regression with SPSS software. Which can be expressed as:

\[
T_{2c} = -10.825 \times (D_{\text{min}} - D_{\text{max}}) + 13.685 \times \left( \frac{D_{\text{min}}}{D_{\text{max}}} \right) - 11.485 \times \text{FZI}
\]

(16)
where the $D_{\text{min}} - D_{\text{max}}$ and $D_{\text{min}}/D_{\text{max}}$ are multifractal parameters, and $FZI$ is the flow zone index.

The positive correlation coefficient of the model is 0.84. The $T_2$ cutoff value of 10 sandstone samples from adjacent blocks is calculated by using the established mathematical equation. The sample information for testing the model is shown in Table 4 and Figure 15. Comparing the $T_2$ cutoff value calculated by Equation 16 with that measured by centrifugal experiment, it can be seen that the intersection point of $T_2$ cutoff value obtained by these two methods almost falls on the intersection line and the slope of the fitting curve is 0.9897 (Figure 16), compared with 1, the relative error is 1.03%, which both represent that the two sides are in good agreement with each other. Therefore, the $T_2$ cutoff value prediction model is definitively accurate and reliable and has practical significance.

Previous studies have established many $T_2$ cutoff value prediction models, but most of them need to add a lot of complex experimental tests under the condition of mastering basic parameters. For example, reservoir porosity and permeability, which vary from place to place, makes it difficult for the model to be widely used. Some researchers have also proposed $T_2$ cutoff value prediction models based on multifractal parameters. However, there are only multifractal parameters in the prediction model. As

### Table 4 Information of sandstone samples used for examining the NMR $T_2C$ prediction model

| Samples | $\Phi$ ( helium) (%) | $K$ ( helium) (mD) | FZI | $D_{\text{min}} - D_{\text{max}}$ | $D_{\text{min}}/D_{\text{max}}$ | $T_2C$ -NMR (ms) |
|---------|----------------------|-------------------|-----|-----------------|-----------------|-----------------|
| 1#      | 3.90                 | 0.25              | 1.97| 1.90            | 3.51            | 3.86            |
| 2#      | 6.08                 | 0.56              | 1.48| 1.83            | 3.27            | 7.22            |
| 3#      | 12.00                | 0.04              | 0.13| 2.24            | 3.89            | 26.15           |
| 4#      | 11.60                | 2.90              | 1.20| 2.17            | 3.75            | 12.30           |
| 5#      | 4.0                  | 0.90              | 3.60| 1.90            | 4.70            | 3.15            |
| 6#      | 6.55                 | 1.02              | 1.78| 2.09            | 3.57            | 2.98            |
| 7#      | 3.50                 | 0.13              | 1.68| 1.16            | 2.73            | 4.82            |
| 8#      | 3.58                 | 0.41              | 2.88| 2.68            | 5.91            | 16.01           |
| 9#      | 2.80                 | 0.11              | 2.19| 2.16            | 4.01            | 4.64            |
| 10#     | 6.50                 | 0.32              | 1.00| 2.44            | 5.63            | 40.01           |

![Figure 15](image1.png)  
**Figure 15** $T_2$ cutoff values of 10 samples used for testing models obtained by NMR centrifugal experiments. A, sample1 ~ 5. B, sample6 ~ 10

![Figure 16](image2.png)  
**Figure 16** Cross plot of the $T_2$ cutoff value from NMR experiment and the $T_2$ cutoff value based on calculation model

The positive correlation coefficient of the model is 0.84. The $T_2$ cutoff value of 10 sandstone samples from adjacent blocks is calculated by using the established mathematical equation. The sample information for testing the model is shown in Table 4 and Figure 15. Comparing the $T_2$ cutoff value calculated by Equation 16 with that measured by centrifugal experiment, it can be seen that the intersection point of $T_2$ cutoff value obtained by these two methods almost falls on the intersection line and the slope of the fitting curve is 0.9897 (Figure 16), compared with 1, the relative error is 1.03%, which both represent that the two sides are in good agreement with each other. Therefore, the $T_2$ cutoff value prediction model is definitively accurate and reliable and has practical significance.

Previous studies have established many $T_2$ cutoff value prediction models, but most of them need to add a lot of complex experimental tests under the condition of mastering basic parameters. For example, reservoir porosity and permeability, which vary from place to place, makes it difficult for the model to be widely used. Some researchers have also proposed $T_2$ cutoff value prediction models based on multifractal parameters. However, there are only multifractal parameters in the prediction model. As
mentioned earlier, reservoirs with the same multifractal parameters may have huge differences in pore size, porosity, and $T_2$ cutoff values. Therefore, the parameter closely related to porosity should not be neglected in prediction of $T_2$ cutoff value with multifractal theory. In this study, the $FZI$, a comprehensive index of porosity and permeability, shows a good correlation with $T_2$ cutoff value and is introduced into the $T_2$ cutoff value prediction model to improve the accuracy of the model to some extent. At the same time, the examined result shows that the model can also be used to predict the $T_2$ cutoff value of tight sandstone reservoirs in other areas.

**5 | CONCLUSION**

Based on the multifractal theory, the multifractal characteristics of NMR $T_2$ distribution of selected sandstone samples are analyzed, and the correlation between the $T_2$ cutoff value and the multifractal parameters is investigated. On this basis, a prediction model of $T_2$ cutoff value for sandstone samples in the study area by using multifractal parameters and $FZI$ was established. Following conclusions are drawn:

1) The NMR $T_2$ spectra of water saturated sandstone samples in the study area can be divided into three types: single steeple peak, double steeple peak, and irregular double peak. The distribution ranges of pore radius from type1 to type3 are $1 \text{ nm} \sim 3 \times 10^2 \text{ nm}$, $1 \text{ nm} \sim 10^3 \text{ nm}$, and $1 \text{ nm} \sim 4 \times 10^3 \text{ nm}$, respectively, and show a decreasing tendency.

2) The pore size distribution of sandstone samples in the study area conforms to multifractal characteristics, and there is significant correlation between multifractal parameters $D_q$ and the $T_2$ cutoff value. The symmetrical fractal dimension difference and symmetrical multifractal dimension ratio shows best correlation with the $T_2$ cutoff value. There is no obvious correlation between $\Delta \alpha$ and the $T_2$ cutoff value.

3) The $FZI$ values are positively correlated with the saturation of movable fluids and negatively correlated with the NMR $T_2$ cutoff value and can also be used as an important parameter for predicting the NMR $T_2$ cutoff value.

4) A prediction model of $T_2$ cutoff value for tight sandstone reservoirs is proposed. The test results show that the model is accurate and can be used to predict the $T_2$ cutoff value of tight sandstone reservoirs in different areas.

**ACKNOWLEDGMENT**

We acknowledge the support from the National Natural Science Foundation of China (No. 41772130), the National Basic Research Program of China (973 Program, No. 2012CB214702) and the Key Laboratory of Coalbed Methane Resources and Reservoir Formation Process of the Ministry of Education (China University of Mining and Technology)(No. 2019-0010). The Changqing Oilfield Company of Petro China provided all the related core samples and some geological data.

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**REFERENCE**

1. Clarkson CR, Jensen JL, Pedersen PK, Freeman M. Innovative methods for flow-unit and pore-structure analyses in a tight siltstone and shale gas reservoir. AAPG Bull. 2012;96(2):355-374.
2. Chen Y, Qin Y, Wei C, et al. Porosity changes in progressively pulverized anthracite subsamples: Implications for the study of closed pore distribution in coals. Fuel. 2018;225:612-622.
3. Loucks RG, Reed RM, Ruppel SC, Jarvis DM. Morphology, genesis, and distribution of nanometer-scale pores in siliceous mudstones of the mississippian barnett shale. J Sediment Res. 2009;79(12):848-861.
4. Lu GW, Wei CT, Wang JL, Yan GY, Zhang JJ, Song Y. Methane adsorption characteristics and adsorption model applicability of tectonically deformed coals in the Huabei coalfield. Energy Fuels. 2018;32(7):7485-7496.
5. Sok RM, Varslot T, Ghaus A, Latham S, Sheppard AP, Knackstedt MA. Pore scale characterization of carbonates at multiple scales: integration of micro-CT, BSEM, and FIBSEM International Symposium of the Society-of-Core-Analysts, SEP 27–30. Noordwijk, the Netherlands. 2009;51(6):379-387.
6. Desbois G, Urai JL, Kokla PA, Konstanty J, Baerle C. High-resolution 3D fabric and porosity model in a tight gas sandstone reservoir: a new approach to investigate microstructures from mm- to nm-scale combining argon beam cross-sectioning and SEM imaging. J Pet Sci Eng. 2011;78(2):243-257.
7. Lu G, Wei C, Wang J, Zhang J, Quan F, Tamehe LS. Variation of surface free energy in the process of methane adsorption in the nanopores of tectonically deformed coals: a case study of middle-rank tectonically deformed coals in the Huabei Coalfield. Energy Fuels. 2019;33(8):7155-7165.
8. Hemes S, Desbois G, Urai JL, Schröppel B, Schwarz J-O. Multi-scale characterization of porosity in Boom Clay (HADES-level, Mol, Belgium) using a combination of x-ray µ-CT, 2D BIB-SEM and FIB-SEM tomography. Micropor Mesop Mat. 2015;208:1-20.
9. Chen Y, Qin Y, Li Z, et al. Differences in desorption rate and composition of desorbed gases between undeformed and mylonitic coals in the Zhina Coalfield, Southwest China. Fuel. 2019;239:905-916.
10. Iglauer S, Paluszny A, Blunt MJ. Simultaneous oil recovery and residual gas storage: a pore-level analysis using in situ x-ray micro-tomography. Fuel. 2013;2013(103):905-914.
11. Zhang J, Wei C, Zhao J, Ju W, Chen Y, Tamehe LS. Comparative evaluation of the compressibility of middle and high rank coals by different experimental methods. Fuel. 2019;245:39-51.
12. Xiao L, Li J, Mao Z, et al. A method to determine nuclear magnetic resonance (NMR) $T_2$ cutoff based on normal distribution simulation in tight sandstone reservoirs. Fuel. 2018;225:472-482.
13. Liu Y, Yao Y, Liu D, Zheng S, Sun G, Chang Y. Shale pore size classification: an NMR fluid typing method. Mar Pet Geol. 2018;96:591-601.
14. Jarvie DM, Hill RJ, Ruble TE, Pollastro RM. Unconventional shale-gas systems: the mississippian Barnett shale of North-Central Texas as one model for thermogenic shale-gas assessment. *AAPG Bull*. 2007;91(4):475-499.

15. Loucks RG, Reed RM, Ruppel SC, Hammes U. Spectrum of pore types and networks in mudrocks and a descriptive classification for matrix-related mudrock pores. *AAPG Bull*. 2012;96(6):1071-1098.

16. Hinai AA, Rezaee R, Esteban L, Labani M. Comparisons of pore size distribution: a case from the Western Australian gas shale formations. *J Unconv Oil Gas Resour*. 2014;8:1-13.

17. Yao Y, Liu D. Comparison of low-field NMR and mercury intrusion porosimetry in characterizing pore size distributions of coals. *Fuel*. 2012;95:152-158.

18. Sun X, Yao Y, Liu D, Zhou Y. Investigations of CO2-water wettability of coal: NMR relaxation method. *Int J Coal Geol*. 2018;188:38-50.

19. Ge X, Fan Y, Zhu X, Chen Y, Li R. Determination of nuclear magnetic resonance T2 cutoff value based on multifractal theory — an application in sandstone with complex pore structure. *Geophys*. 2015b;80(1):11-21.

20. Timur A. pulsed nuclear magnetic resonance studies of porosity, movable fluid, and permeability of sandstones. *J Pet Technol*. 1969;21(06):775-786.

21. Zheng S, Yao Y, Liu D, Cai Y, Liu Y. Characterizations of full-scale pore size distribution, porosity and permeability of coals: a novel methodology by nuclear magnetic resonance and fractal analysis theory. *Int J Coal Geol*. 2018;196:148-158.

22. Zhao Y, Zhu G, Dong Y, Danesh NN, Chen Z, Zhang T. Comparison of low-field NMR and microfocus x-ray computed tomography in fractal characterization of pores in artificial cores. *Fuel*. 2017;210:217-226.

23. Xu J, Zhai C, Liu S, Qin L, Wu S. Pore variation of three different metamorphic coals by multiple freezing-thawing cycles of liquid CO2 injection for coalbed methane recovery. *Fuel*. 2017;208:41-51.

24. Timur A. Nuclear magnetic resonance study of carbonate rocks. *Log Analyst*. 1991;13:518-535.

25. Coates GR, Xiao LZ, Primmer MG. NMR logging principles and applications. Gulf: Publishing Company; 2000.

26. Mai A, Kantzas A. An evaluation of the application of low field NMR in the characterization of carbonate reservoirs. *SPE Annual Technical Conference and Exhibition*. 2002; SPE-77401-MS.

27. Zhang GQ, Hirasaki GJ, House WV. Internal field gradients in porous media. *Petrophysics*. 2003;44:422-434.

28. Yao Y, Liu D, Che Y, Tang D, Tang S, Huang W. Petrophysical characterization of coals by low-field nuclear magnetic resonance (NMR). *Fuel*. 2010, 89(7), 1371-1380.

29. Godefroy S, Fleury M, Deflandre F, Korb JP. Temperature effect on NMR surface relaxation; *SPE Annual Technical Conference and Exhibition*, SPE/17100, 2001.

30. Wang Z, Zhan C, Xiao C, Chen X, Song F. Experimental study of T2 cutoff values in low-permeability reservoirs. *Prog Geophys*. 2004, 19(3), 652-655. Published in China.

31. Westphal H, Surholt I, Kiesl C, Thern HF, Kruspe T. NMR Measurements in Carbonate Rocks: Problems and an Approach to a Solution. *Pure Appl Geophysics*. 2005;162(3):549-570.

32. Gao C, He Z, Wu H, Li M. Relationship between NMR T2 cutoff and capillary pressure. *Oil Geophys Prospect*. 2004, 39(1), 117-120. Published in China.

33. Ge X, Fan Y, Deng S. Research on T2 cutoff value determination method for shaly sand based on experiment. *Well Log Technol*. 2012, 35(4), 308-313. Published in China.

34. Nicot B, Ligneul P, Akbar M. T2 cutoff determination using magnetic susceptibility measurements: U. S. Patent Application. US20130265043A1.

35. Clarkson CR, Solano N, Bustin RM, et al. Pore structure characterization of North American shale gas reservoirs using USANS/SANS, gas desorption, and mercury intrusion. *Fuel*. 2013;103:606-616.

36. Yang F, Ning Z, Liu H. Fractal characteristics of shales from a shale gas reservoir in the Sichuan Basin, China. *Fuel*. 2014;115:378-384.

37. Liu X, Xiong J, Liang L. Investigation of pore structure and fractal characteristics of organic-rich Yanchang formation shale in central China by nitrogen desorption analysis. *J Nat Gas Sci Eng*. 2015;22:62-72.

38. Mandelbrot BB. The fractal geometry of nature, rev. and enlarged ed. New York: W. H. Freeman and Co.; 1989, 495.

39. Jiang F, Chen D, Chen J, et al. Fractal analysis of shale pore structure of continental gas shale reservoir in the Ordos Basin, NW China. *Energy Fuels*. 2016;30(6):4676-4689.

40. Lu GW, Wang JL, Wei CT, et al. Pore fractal model applicability and fractal characteristics of seepage and adsorption pores in middle rank tectonic deformed coals from the Huaibei coal field. *J Pet Sci Eng*. 2018;171:808-817.

41. Yu S, Bo J, Jie-gang L. Nanopore structural characteristics and their impact on methane adsorption and diffusion in low to medium tectonically deformed coals: case study in the Huaibei Coal Field. *Energy Fuels*. 2017;31(7):6711-6723.

42. Gould DJ, Vadakkan TJ, Poché RA, Dickinson ME. Multifractal and lacunarity analysis of microvascular morphology and remodeling. *Microcirculation*. 2011;18(2):136-151.

43. Zhang Z, Weller A. Fractal dimension of pore-space geometry of an Eocene sandstone formation. *Geophysics*. 2014;79(6):377-387.

44. Bu H, Ju Y, Tan J, Wang G, Li X. Fractal characteristics of pores in non-marine shales from the Huanain Coalfield, Eastern China. *J Nat Gas Sci Eng*. 2015;24:166-177.

45. Grassberger P. Generalized dimensions of strange attractors. *Phys Lett A*. 1983;97(6):227-230.

46. Li L, Chang L, Ke S, Huang D. Multifractal analysis and lacunarity analysis: a promising method for the automated assessment of muskmelon (Cucumis melo L.) epidermis netting. *Comput Electron Agr*. 2012;88:72-84.

47. Zhao P, Wang Z, Sun Z, Cai J, Wang L. Investigation on the pore structure and multifractal characteristics of tight oil reservoirs using NMR measurements: Permian Lucaogou formation in Jimusaer Sag, Junggar Basin. *Mar Pet Geol*. 2017;86:1067-1081.

48. Li W, Liu H, Song X. Multifractal analysis of Hg pore size distributions of tectonically deformed coals. *Int J Coal Geol*. 2015;144-145:138-152.

49. Wei W, Cai J, Hu X, et al. A numerical study on fractal dimension of current streamlines and three-dimensional pore fractal models of porous media. *Fractals*. 2015;23(01):1540012.

50. Liu K, Ostadahassan M. Quantification of the microstructures of bakken shale reservoirs using multi-fractal and lacunarity analysis. *J Nat Gas Sci Eng*. 2017;39:62-71.

51. Vázquez EV, Ferreiro JP, Miranda JGV, González AP. Multifractal analysis of pore size distributions as affected by simulated rainfall. * Vadose Zone J*. 2008;7(2):500-511.
52. Ge X, Fan Y, Li J, Aleem Zahid M. Pore structure characterization and classification using multifractal theory—an application in Santanghu Basin of Western China. *J Petrol Sci Eng*. 2015a;127:297-304.

53. Ferreiro JP, Vázquez EV. Multifractal analysis of Hg pore size distributions in soils with contrasting structural stability. *Geoderma*. 2010;60(1):64-73.

54. Ge X, Fan Y, Zhu X, Chen Y, Li R. Determination of nuclear magnetic resonance T₂ cutoff value based on multifractal theory—an application in sandstone with complex pore structure. *Geophysics*. 2015;80(1):11-21.

55. Economic S, Commission T. *Formation damage evaluation by flow test: SY/T 5358–2010*. Beijing: Petroleum Industry Press; 2010:1-32.

56. National Energy Board. *Specification for measurement of rock NMR parameter in laboratory: SY/T 6490–2014*. Beijing: Petroleum Industry Press; 2015.

57. Mandelbrot BB, Kol B, Aharony A. Angular gaps in radial diffusion-limited aggregation: two fractal dimensions and non-transient deviations from linear self-similarity. *Phys Rev Lett*. 2002;88(5).

58. Leonelli G, Paladin G, Viezzoli G. Technical aspects of digital processing and transmission of x-ray pictures. *Rays*. 1991;16(4):477-486.

59. Paz Ferreiro J, Vidal Vázquez E. Multifractal analysis of Hg pore size distributions in soils with contrasting structural stability. *Geoderma*. 2010;160(3–4):373-385.

60. Gutierrez CG, Jose FS. Multifractal analysis of soil micro and macro porosity using digital images obtained with fluorescent dye. *Geophys Res Abs*. 2006;8:11094.

61. Martínez FSI, Martína MA, Caniego FJ, et al. Gutiérrez Multifractal analysis of discretized x-ray CT images for the characterization of soil micro-pore structures. *Geoderma*. 2010;156:32-42.

62. Chhabra A, Jensen RV. Direct determination of the f(α) singularity spectrum. *Phys Rev Lett*. 1989;62(12):1327-1330.

63. Kenyon WE. Nuclear magnetic resonance as petro-physical measurement. *Int J Radiat Appl Instrum E: Nucl Geophys*. 1992;6(2):153-171.

64. Fang T, Zhang L, Liu N, et al. Quantitative characterization of pore structure of tight gas sandstone reservoirs by NMR T2 spectrum technology: a case study of Carboniferous Permian tight sandstone reservoir in Linqing depression. *Acta Petrol Sin.* 2017, 38(8), 902-915. Published in China.

65. Lee CK. Multifractal characteristics in air pollutant concentration time series. *Water Air Soil Pollut*. 2002;135(1–4):389-409.

66. Miranda JGV, Montero E, Alves MC, Paz González A, Vidal Vázquez E. Multifractal characterization of saprolite particle-size distributions after topsoil removal. *Geoderma*. 2006;134(3–4):373-385.

67. Martín MA, Rey JM, Taguas FJ. An entropy-based parametrization of soil texture via fractal modelling of particle-size distribution. *P Roy Soc A-Math Phy Eng Sci*. 2001;457:937-947.

68. Zheng S, Yao Y, Liu D, Cai Y, Liu Y, Li X. Nuclear magnetic resonance T₂ cutoffs of coals: a novel method by multifractal analysis theory. *Fuel*. 2019;241:715-724.

**How to cite this article:** Hu Y, Guo Y, Zhang J, et al. A method to determine nuclear magnetic resonance T₂ cutoff value of tight sandstone reservoir based on multifractal analysis. *Energy Sci Eng*. 2020;8:1135-1148. [https://doi.org/10.1002/ese3.574](https://doi.org/10.1002/ese3.574)