A comprehensive study on geometric, topological and fractal characterizations of pore systems in low-permeability reservoirs based on SEM, MICP, NMR, and X-ray CT experiments

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ABSTRACT

Characterization of pore systems in subsurface systems is of great importance for predicting the properties of rocks and classifying the subsurface systems. Geometric features have been used widely for this aim, but topological characteristics of the pore structures are not studied much. In fact, accurate characteristics of pore space should comprise both its geometric and topological properties. In this paper, the above vital characteristics are comprehensively studied based on direct experimental results. Besides, previous studies aiming at linking fractal dimension analysis to pore space are often based on limited sources of information, which are the mercury injection capillary pressure (MICP) and nuclear magnetic resonance (NMR). In this paper, the scanning electron microscope (SEM), MICP, NMR, and X-ray computed tomography (X-ray CT) experiments are all used to characterize the geometric and topological properties of pore space of several low-permeability porous media. Based on our observations, the advantages and disadvantages of the above techniques in characterizing the pore structure are also summarized. Moreover, the differences of these three experiments are quantified using fractal dimension. The results indicate that the NMR technique is a promising tool for characterizing geometric features of pore systems as it can cover more details than other techniques. Most of geometric, topological, fractal and transport properties of pore space can be obtained from X-ray CT method, which is unique among all the methods. In addition, the 3D fractal dimensions of pore systems obtained from NMR is smaller than that from MICP, which is due more ultra-micropores captured by NMR that smooth the surface of the pore systems. Finally, a novel method constrained by a new pore shape factor for calculating the pore-size distributions are compared more effectively.

1. Introduction

In subsurface characterization, finding the high-quality and permeable regions (e.g. sweet spots of reservoirs) is very crucial (Clarkson et al., 2013; Nelson, 2011, 2009; Tahmasebi et al., 2017; Xiao et al., 2017). The quality of the reservoirs was affected by many macroscopic factors, such as depth, porosity, and permeability of the reservoirs, hydrocarbon content, and hydrocarbon quality in the reservoirs. In fact, most of these macroscopic properties of reservoirs (e.g. porosity and permeability) are mainly controlled by the microscopic petrophysical properties of the rocks, such as the features of pore systems (Blunt et al., 2013; Daigle et al., 2017; Daigle and Dugan, 2011; Fagbemi et al., 2018b, 2018a; Hu et al., 2017, 2012; Hu and Brusseau, 1994; Jiang, 2008; Tahmasebi and Kamrava, 2018; Xiong et al., 2016). As such, the characterization of pore systems is of great importance for porous media modeling. The pore structure properties of porous media include the geometrical and topological characteristics (Jiang, 2008). For the reservoirs with few or no fractures, the geometrical properties of pore space consist of volume, surface area, radius and shape of the pores and throats. The topological parameters comprise the connectivity, tortuosity, Euler number, coordination number, and two-point correlation function. As to the fractured reservoirs, such as shales and coal seams, the characterization of pore systems should include the description and measurement of the fractures in the rock because the
fractures also make a considerable effect on the macroscopic properties of the rocks (Clarkson and Bustin, 1996; Ramandi et al., 2018, 2016a; 2016b; Tan et al., 2018; Zhang et al., 2019).

To date, numerous techniques have been presented to describe and characterize the pore structures of porous media (Gao et al., 2019; Hu Sun et al., 2018), have been widely used to acquire pore-space properties. These methods can be divided into two groups, namely direct imaging measurements and indirect techniques. The former represents a set of methods by which the pore structure features are directly analyzed and characterized using imaging techniques, such as various microscopes, X-ray computed tomography (X-ray CT) (Huang et al., 2015; Peng et al., 2012; Wu et al., 2018; Zhang et al., 2016) and laser scanning confocal instruments (Minsky, 1988). The images obtained from these techniques can be two- and three-dimensional. These imaging tools are the optical microscope, common scanning electron microscope (SEM) (Henares et al., 2014), back-scattered scanning electron microscope (BSEM) (Latham and Bustin, 2018; Li et al., 2018; Van Geet et al., 2001; White et al., 1984), transmission electron microscopy (TEM) (Chalmers et al., 2012), environmental scanning electron microscope (ESEM) (Romero and Simms, 2008), field-emission scanning electron microscopy (FE-SEM) (Chalmers et al., 2012), focused ion beam scanning electron microscope (FIB-SEM) (Tahmasebi et al., 2015; Zhang et al., 2017) and broad ion beam scanning electron microscope (BIB-SEM) (Hemes et al., 2015; Norbisrath et al., 2015). Each microscope has its specific pros and cons, which is determined by imaging principle and work performance of the microscope. Owing to the availability of 2D SEM images, some researchers measured the pore size distribution based on 2D images. However, several assumptions need to be taken into account when the imaging is limited to 2D sections. For example, often the shape of pores is assumed as a circle for evaluating the pore size pore distribution (Pengfei et al., 2018; Su et al., 2018), which clearly is unreasonable (Dong and Blunt, 2009). In our research, thus, a novel method constraint by the pore shape factor for calculating the pore radius will be proposed.

On the other hand, the indirect measurement techniques, for example, mercury injection capillary pressure (MICP) (Favvas et al., 2009; Lai et al., 2018a; Okolo et al., 2015), nuclear magnetic resonance (NMR) (Lai et al., 2018b; Li et al., 2015; Yao et al., 2010), gas (i.e. N₂ and CO₂) adsorption (Favvas et al., 2009) and small-angle neutron scattering (SANS) (Favvas et al., 2009; Radlinski and Mastalerz, 2017; Sun et al., 2018), have been widely used to acquire pore-space properties. 2D SEM imaging method can obtain high-resolution details of pore system, but it only covers a small field of view in the sample and cannot fully describe the realistic geometric and topological characteristics of 3D pore space. In contrast, the indirect measurement techniques can capture such information regarding the 3D pore structure of a large sample.

The previous studies about pore system characterization are mostly focused on the geometric characteristics of pores using one type of technique or a combination of some techniques of SEM, MICP, NMR, N₂ adsorption, SANS, and X-ray CT (Fink et al., 2018; Lai et al., 2018b; Sarkar et al., 2018; Zhang et al., 2016), but the analyses of the topological features of the pore systems are often neglected. Whereas, the topological parameters such as coordination number and tortuosity also have a very significant influence on the transport properties (Cai and Yu, 2011). Hence, in this work, the topological features of the pore system will be given more attention to. In addition, the advantages and disadvantages of calculating the pore radius from SEM, MICP, NMR and X-ray CT will also be summarized.

The fractal theory has been widely used in many fields including geology, materials science, architecture, economic management, biology, medicine and soil science (Cai et al., 2015; Daigle et al., 2014; Ge et al., 2016; Li et al., 2017; Mandelbrot and Wheeler, 1983). The differences between the fractal theory and the traditional classical Euclidean geometry are that the dimension of the classical geometry is an integer, such as 1 and 2, but the dimension of fractal geometry can be a decimal (Ge et al., 2016). Fractal theory can describe complex and irregular geometry whereas traditional geometry cannot characterize. On the topic of our paper for pore structure, several studies have been done based on the MICP, NMR and CT experiments (Cai et al., 2015; Ge et al., 2016; Lai et al., 2018b; Serrano et al., 2013). For example, Li (2010) proposed to calculate the fractal dimension of the pore structure with the help of MICP test (Li, 2010). This method is criticized elsewhere (Ge et al., 2016; Lai et al., 2018b; Liu et al., 2017; Sun et al., 2018). Ge et al. (2015) used the NMR data to analyze the fractal characteristics and evaluate reservoir quality (Ge et al., 2015). Cai et al., 2015 made a review about fractal modeling of permeability for porous media (Cai et al., 2015). However, their studies are mostly based on one technique of MICP and NMR (Lai and Wang, 2015; Li et al., 2017). The benefits and drawbacks of calculating the fractal dimension of pore structure based on MICP, NMR and CT have not yet been compared and studied. Thus, in this paper, an accurate formula derivation about computing the fractal dimension of pore space from MICP and NMR will be presented. Moreover, we analyze the fractal dimension of the pore structure from MICP, NMR, and X-ray CT tests and the results from these three methods will be discussed accordingly.

In this study, in order to fully characterize the geometrical and topological properties and analyze the fractal dimension of the pore structure of the porous media, a variety of experiments, including SEM, MICP, low field NMR and X-ray CT, are conducted on five samples from the Shahejie formation in the Wangjiagang field, Dongying depression, Bohai Bay Basin, China. The rest of this paper is organized as follows: Section 2 gives a brief introduction of the geological background while Section 3 mainly describes the utilized samples and the processes of our experiments. Section 4 consists of two parts, where the first part will demonstrate the methodologies, results and pros and cons of calculating geometrical and topological properties based on SEM, MICP, NMR, and X-ray CT techniques. As to the second part, the formula derivation about calculating the fractal dimension of the pore structure will be given, and discussions about the results of the fractal dimension from different techniques are presented. A summary of our findings will be given in Section 5.

2. Geological background

In this study, five low-permeability sandstone samples are collected from Es4s of the Shahejie formation in the Wangjiagang field, Dongying depression, Bohai Bay Basin, China, which is located in the south of the Bohai Bay Basin of China, shown in Fig. 1. The Eocene Shahejie Formation (Es) contains the main source and reservoir rocks. The organic matter of the source is dominated by type I kerogens (oil prone) and Es has four major divisions; Es4, Es3, Es2, and Es1 (from bottom to top). The organic-rich lowermost interval (Es4) is further divided into upper (Es4u) and lower parts (Es4l). Es4u consists of interbedded turbiditic fan sandstones deposited in a semi-deep and deep lacustrine environment. Es4s is composed of gray to brown-gray and black mudstones, shales, dolomites, and turbiditic fan sandstone interbeds which are deposited in a semi-deep and deep lacustrine environment. Es4d is deposited in variable depth ranges from 1500 m to 2800 m in different sub-depressions of the Dongying Depression having overall depth ranges. More detail about the sequence stratigraphy and sedimentary facies of Es4s, Wangjiagang field, Dongying Depression, Bohai Bay Basin can be found in Zahid (Zahid et al., 2016). In order to characterize and analyze the pore system of Es4s beach-bar reservoir, five samples, representing characteristic beach-bar reservoir, were chosen to perform the SEM, MICP, low field NMR experiment, and one sample was studied using X-ray CT scanning.
3. Experiments

3.1. Sample collection and preprocessing

The basic information of the five experimental samples is shown in Table 1. These core samples represent a specific but to the heterogeneous nature of the samples. SEM, MICP and NMR tests were implemented on all these samples. Especially, X-ray CT experiment was carried out for S5. Regarding sample preprocessing, the remnants of the reservoir fluids and the drilling mud caused by the mud invasion should be cleaned before the experiments. After cutting and polishing, samples are reshaped into cylinders with the diameter of 2.5 cm and the length of 5 cm for NMR. After we conducted NMR experiments, these cylinders were cut into two small cylinders with the length of 3 cm and 1.8 cm, respectively. These cylinders with the length 3 cm are used for MICP tests. The others were prepared for the SEM experiments. For S5, a tiny cylinder with the diameter 3 mm and the length of 1 cm that was extracted from the small cylinder with the length of 1.8 cm was used for X-ray CT.

Table 1
Information of samples and the experimental methods.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Well</th>
<th>Depth (m)</th>
<th>Analyses</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>W122</td>
<td>2812.2</td>
<td>SEM, MICP, NMR</td>
</tr>
<tr>
<td>S2</td>
<td>W125</td>
<td>2798.5</td>
<td>SEM, MICP, NMR</td>
</tr>
<tr>
<td>S3</td>
<td>W149</td>
<td>1686.1</td>
<td>SEM, MICP, NMR</td>
</tr>
<tr>
<td>S4</td>
<td>W149</td>
<td>1689.7</td>
<td>SEM, MICP, NMR</td>
</tr>
<tr>
<td>S5</td>
<td>F142</td>
<td>3116.2</td>
<td>SEM, MICP, NMR, X-ray CT</td>
</tr>
</tbody>
</table>

3.2. Experiments

3.2.1. SEM experiment

SEM is a commonly used direct method to separate pore types, observe pore morphology and calculate pore radius (Nelson, 2009). Although one 2D SEM image only reveals one cross-section pore morphology of a three-dimensional (3D) pore geometry, it is easy to obtain, and it can reflect plenty of information about the pore structures. Therefore, it is still a popular method to characterize the features of pore space. The SEM experiment was carried out at State Key Laboratory of Heavy Oil, China University of Petroleum (East China). The steps of SEM experiment consist of polishing, milling by high-energy argon ion beaming, coating a conductive carbon film on the sample surface and observing using the electron microscopy. SEM images were photographed using the Hitachi S-4800 SEM.

3.2.2. MICP experiment

MICP is a popular indirect method for measuring pore and throat size distributions (Okolo et al., 2015; Yao and Liu, 2012). The MICP experiment in our research was conducted at China National Petroleum Corporation (CNPC) Key Well Logging Laboratory, China University of Petroleum (East China) using AutoPore™ IV9510 (Micromeritics Instrument Corporation). The sample with a diameter of 2.5 cm was first washed for removing the oil and then dried at 95 °C for 48 h and subjected to a vacuum. Finally, liquid mercury was injected into the sample with the pressure from 0 to 207 MPa while the amount of mercury into the rock under different pressures is recorded.

3.2.3. NMR experiment

The NMR method has been widely used in pore structure analysis (Lai et al., 2018b; Li et al., 2015; Yao et al., 2010; Yao and Liu, 2012). The detailed principle is shown in Lai et al. (2018b). The NMR
experiment in our research was conducted at China National Petroleum Corporation (CNPC) Key Well Logging Laboratory, China University of Petroleum (East China). First, five samples were dried for 24 h at 95 °C to remove the fluid in the pore space and subjected to a vacuum. Then, these samples were fully saturated with brine and centrifuged to reach the bound water status. Meanwhile, the NMR T2 relaxation time was measured on brine saturated and irreducible saturated core plugs using the MARAN-II ultra-rock spectrometer (Oxford Instrument Incorporation).

3.2.4. X-ray CT experiment

With the rapid development of X-ray CT equipment, CT has been applied to more and more industries (Blunt et al., 2013; Bultreys et al., 2016; Mathews et al., 2017; Ren et al., 2015; Thompson et al., 2016; Wang et al., 2008). The major advantage of the X-ray CT method is that it can perform three-dimensional, non-destructive imaging (Chengyan et al., 2018). Many petroleum geologists have used CT equipment to analyze the pore structure inside the cores. The technique is not only beneficial to preserve the precious core but also can be used to describe the realistic three-dimensional pore system of porous media (Chengyan et al., 2018). Due to it, the digital core analysis got rapid development. In our study, SS was selected for X-ray CT experiment. 2020 CT to-mograms were obtained using the FEI HeliScanTM helical μ-CT imaging facility in Canberra. During the scanning process, the X-ray source and the detector remain stationary and the images of different angles were obtained by rotating the turn table. The turn table were moved according to a pre-defined helical trajectory, along which a series of radiographs were recorded uniformly around the sample at different viewing angles (Ramandi et al., 2016a; Sheppard et al., 2014). The resolution of the images is 2.4 μm per voxel. The digital core analysis will be explained in the following sections.

Fig. 2. Workflow of calculating the pore size from S1 SEM image using PRCSF.
4. Methodologies, results and discussion

4.1. Geometric and topological characteristics of pore system

4.1.1. Pore space features from SEM

4.1.1.1. Methodology. For 2D images, the conventional methodology of calculating the pore radius is to assume the pores as the equivalent circles and get pore size \( r = \sqrt{\frac{A}{P}} \) (1) where \( A \) is the area of the pore (Pengfei et al., 2018; Su et al., 2018). In fact, many pores in 2D images are not circular. To get a more realistic result, a novel method is proposed to compute the pore size from 2D slices which is called pore radius calculation based on shape factor (PRCSF). The detailed steps are as follows:

A) Binarize SEM images to obtain the pore space using the thresholding method, perform the median filter to reduce the noises and apply the watershed algorithm to separate the connected pores and calculate the area and perimeter of each pore.

B) Obtain the shape factor \( G \) of the pore using \( G = \frac{A}{P} \) (2), where \( A \) and \( P \) is the area and perimeter of the pore, respectively. The shape factor is a common parameter for characterizing the pore morphology (Dong and Blunt, 2009). The larger the shape factor, the smoother the pore tends to be and the closer the pore is to circle. Furthermore, the pore shape factor is also a vital parameter for computing the permeability of the rock using the high-resolution images.

C) For the equilateral triangle, square, and circle, the shape factors are 0.0481, 0.071, and 0.0796, respectively. To accurately get the hydraulic radius of the pores, the pores are equated with circular, square and triangular pores according to \( G \), respectively. Then the corresponding radius calculation formulas are used to extract the radii of the inscribed circle of the equivalent pores as their pore radii. Taking the S1 sample as an example, the workflow of PRCSF is shown in Fig. 2 schematically.

4.1.1.2. Pore size distribution from SEM. The pore size distributions of S1-S5 were computed based on the PRCSF algorithm and the results are displayed in Fig. 3. As can be seen, the pore size distributions of S1 and S2 are bimodal. For S1-S4, there are small proportions of small pores (less than 1 \( \mu m \)) in the pore system, the minimum pore radii of them are 0.2 \( \mu m \), which is the resolution of SEM images, and their maximum pore radii are distributed from 8 to 10 \( \mu m \). Besides, all of the curves show that the main pore radii of S5 are larger than the primary pore radii of other samples. Moreover, the corresponding pore radii of their peaks corresponding to S1, S2, S3, S4, and S5 are 4.05 \( \mu m \), 3.29 \( \mu m \), 3.02 \( \mu m \), 2.35 \( \mu m \) and 4.99 \( \mu m \), respectively.

4.1.2. Pore space features from MICP

MICP curves of the five samples are shown in Fig. 4. Inspecting the results shows that more mercury gets into S5 when the pressure reaches 1 MPa, which indicates that there are many large pores in this sample.

4.1.2.1. Methodology. According to the classical capillary pressure theory, pore-throat radius (called pore radius hereafter) can be obtained from the varied pressure as:

\[
R = \frac{2\sigma \cos \theta}{Pc(S_Hg)}
\]

where \( \sigma \) is the interfacial tension (0.48 N/m for a mercury/air system). \( Pc \) is capillary pressure. \( \theta \) is contact angle, 42.8° from the experiment measure and \( S_Hg \) is mercury saturation. Then, the probability distribution function pdf of pore radius can be calculated using (Alyafei et al., 2016):

\[
PDF = R \frac{dS_Hg}{dR} = -R \frac{dS_Hg}{dPc} = \frac{dS_Hg}{dlnPc} \tag{4}
\]

Using Eq. (4), pore radius distributions of all the samples are calculated and the results are shown in Fig. 5. It is manifested from Fig. 5 that the pore distributions of S1, S2 and S4 have similar characteristics and pore volume fraction of their peaks are all more than 0.15 while the scores of S4 and S5 are around 0.1. The major pore radii of S1, S2 and S4 are more concentrated at 1.8–3.7 \( \mu m \), 1.2–2.4 \( \mu m \) and 2.7–3.8 \( \mu m \), respectively. Besides, the average pore radii of S1-S5 derived from MICP are 1.68 \( \mu m \), 1.36 \( \mu m \), 0.28 \( \mu m \), 2.18 \( \mu m \), and 2.67 \( \mu m \), respectively.

4.1.2.2. Pore size distribution from MICP. In this research, according to the pore size distribution characteristics and fractal dimension features of pore space, the pores are divides into macropores, mesopores, micropores, and ultra-micropores. The fractal dimension of different pores will be described in detail. The radii of macropores, mesopores, micropores and ultra-micropores are more than 5 \( \mu m \), 1–5 \( \mu m \), 0.1–1 \( \mu m \) and less than 0.1 \( \mu m \), respectively. Porosity in each of the above group was computed and listed in Table 2. It can be observed that the macropores in S5 have a higher proportion than other samples. The percentage of mesopores for S1, S2, S4, and S5 are more than 40%, which implies many pores are mesopores.

![Fig. 3. Pore area distributions of S1-S5 obtained from the SEM images using PRCSF.](image-url)
4.1.3. Pore space features from NMR

The NMR experimental results are displayed in Fig. 6. It can be observed that there are two peaks for all the samples. The change of incremental porosity with the relaxation time ($T_2$) from S1 and S3 is similar. The pore size distributions will be approximately obtained from these figures, which will be described below.

4.1.3.1. Methodology

Regarding low field NMR, transverse relaxation time $T_2$ consists of bulk relaxation time ($T_{2B}$), diffusion relaxation time ($T_{2D}$) and surface relaxation time ($T_{2S}$):

$$\frac{1}{T_2} = \frac{1}{T_{2B}} + \frac{1}{T_{2D}} + \frac{1}{T_{2S}}$$

(5)

$T_{2B}$ is usually much larger than $T_2$, so it can be ignored. When using a sufficiently small echo interval, one can simplify Eq. (5) as the following (Zhao et al., 2017):

$$\frac{1}{T_2} = \frac{1}{T_{2S}} = \rho \frac{S}{V}$$

(6)

where $S$ is the pore surface area in $\mu m^2$, $V$ is the pore volume in $\mu m^3$ and $\rho$ is the transversal surface relaxivity in $\mu m/ms$.

The relationship between $S$ and $V$ can be expressed by (Zhao et al., 2017):

$$S = \frac{m}{V}$$

(7)

where $r$ is the pore radius, $m$ is a constant and it is a function of the shape of the pore. Thus, the relationship between the pore radius $r$ and the relaxation time of $T_2$ is as follow (Lai et al., 2018b; Li et al., 2015):

$$r = nT_2$$

(8)

where $n$ is related to $\rho$ and $m$, with the unit of $\mu m/ms$.

One of the issues regarding the NMR technique to characterize the pore structure of the rock is the determination of the coefficient $n$. The coefficient $n$ is generally obtained by comparing the cumulative probability curve of the $T_2$ spectrum of the NMR experiment with the cumulative probability curve of the pore radius from MICP test when two curves are tangent (Analysis et al., 2017).

The coefficient $n$ values of the five samples are determined as shown in Fig. 7. The result is listed in Table 3. As can be clearly seen, the pore radius cumulative probability curves of S5 from NMR and MICP have a big gap representing the heterogeneity of S5.

4.1.3.2. Pore size distribution from NMR. The pore size distributions of

![Fig. 4. The MICP curves of all the samples.](image1)

![Fig. 5. Pore size distributions of S1-S5 from MICP tests.](image2)
all the samples can be acquired by solving Eq. (8), which is shown in Fig. 8. According to Fig. 8, it is demonstrated that the pore size distribution curve of S5 has only one single peak and the curves of other samples are bimodal. For S1-S4, their main pore radii are distributed from 1 to 9 μm and the secondary peaks are distributed from 0.03 to 0.2 μm. The curve of S5 shows that some of the pores are larger than 100 μm, a possible reason for small fractures in the sample. Moreover, the corresponding pore radii of the peaks of S1-S5 are 2.81 μm, 1.23 μm, 2.14 μm, 3.14 μm, and 2.56 μm, respectively. In addition, the proportion of macropores, mesopores, micropores, and ultra-micropores are shown in Table 4. There are similar proportions of different kind of pores between the MICP and NMR tests.

### 4.1.4. Pore space features from X-ray CT

In the CT experiment, the resolution is set to 2.4 μm, so the micropores and ultra-micropores of S5 will not be covered. When it comes to the pore space analysis using X-ray CT technique, the representative elementary volume (REV) is one of the parameters that should be defined ahead. In this paper, based on the porosity change of subvolume with its volume (voxels) that is shown in Fig. 9, a sample with the size of 600 × 600 × 600 voxels is chosen as the REV size. In terms of the processing steps of the CT image, the REV was firstly extracted from the original grayscale CT images, subsequently filtered by median filtering, and segmented using an interactive threshold with the threshold value (11000, under the 16-bit unsigned greyscale) for separating solid (Fig. 10(a)) and pore space (Fig. 10(b)). Next, the closing algorithm was performed on the segmented images to get the smoothed pore space. Finally, the porosity of the REV is 7.67%.

According to whether the pore space is connected or not, the pore space can be divided into connected and isolated pore space (Wu et al., 2018). Connected pore space means pore bodies are connected with other pore bodies by throats. Subsequently, the connected pore space was acquired by operating the connected algorithm. Isolated pore space was also obtained by subtracting the connected pore space from the total pore space, Fig. 10(c). Isolated pore space occupies 3.16% of the total volume and 41.20% of the volume of pore space, which indicates there is the bad connectivity for the pore space of S5. The reason is that macropores and mesopores may be connected by the micropores and ultra-micropores, but the tiny pores are not contained in the pore space from CT test. Besides, the centroid path tortuosity is introduced to characterize the complexity of the pore space. It is defined as the ratio between actual path length of pore space along a direction and the distance of two centroids of the curved pore space. The greater the tortuosity value, the more complicated the pore structure is (Wu et al., 2018). The centroid path tortuosity of S5 is 3.28, which reveals that the existing pore system in S5 is complicated. After the pore space was separated, the pores and throats were distinguished using the maximal ball algorithm (Dong and Blunt, 2009). Moreover, the pore network model of the SS sample was extracted, Fig. 10(d).

In addition, the single-phase fluid flow in pore space was simulated based on the Navier-Stokes and Darcy’s Law. Navier-Stokes equation is expressed as (Tahmasebi, 2018a; Zhang and Tahmasebi, 2018):

\[
\begin{align*}
\mu V^3 V - \nabla P &= 0 \\
\nabla V &= 0
\end{align*}
\]

where \( \mu \) is the fluid viscosity, \( v \) represents the velocity of the fluid and \( p \) represents the pressure. The inlet pressure is 100,000 Pa and the outlet pressure is 80,000 Pa. The fluid viscosity \( \mu \) is set as 0.001 Pa·S. Finally, the effective permeability was calculated to be 16.89 × 10^{-3} m^2.

The coordination number and specific Euler number (SEN) are important parameters for characterizing the topological characteristics. These parameters can describe the connectivity of a specific component in the porous medium (Jiang, 2008). The coordination number distribution was computed using the maximal ball algorithm (Dong and Blunt, 2009) and the results are shown in Fig. 11(a). From the coordination number distribution, it can be obtained that 18.02% pores are isolated while 79.17% pores are connected by 1–5 throats. The maximum of the coordination number is 21, which confirms that there are many small throats around the pore. With regard to SEN, it was first introduced by Vogel and Roth (2001). SEN can overcome the weaknesses of the conventional Euler number (Jiang, 2008). SEN is defined by:

\[
\chi = \frac{N_c}{V^2}
\]

where \( \chi \) is the conventional Euler number of a porous medium with volume \( V \). SEN makes it possible for comparing the connectivity among rock images of different volume (Jiang, 2008). More information about SEN can be found in Vogel and Roth (2001) and Jiang (2008). The SEN curve of S5 is shown in Fig. 11(b), which illustrates that the connectivity of pore space increases as the minimum (> 5.0 μm) diameter of pores decreases. In other words, the pore connectivity increases when the smaller pores are added. Furthermore, two-point correlation function (TPCF) was used to describe the probability of finding two voxels in the 3D models at different positions both in the pore space (Huang et al., 2015; Tahmasebi, 2018b, 2017). The definition of TPCF is:

\[
S(x, x + h) = I(x)I(x + h),
\]

where \( x \) and \( x + h \) are two voxels in the 3D porous media. \( h \) is the magnitude of the vector. \( I(x) \) is an indicator function, \( I(x + h) = 1 \) when in the void space and \( I(x + h) = 0 \) otherwise. \( I(x)I(x + h) \) represents the average of the multiplication of two indicator functions (Wu et al., 2018). From Fig. 11(c), it can be clearly seen that the correlation of two voxels decreases with the increase of their distance. The TPCF curve levels off at 0.0076 when the distance of two voxels is more than 150 μm.

In terms of pore geometry system of S5, distributions of the pore and throat size, pore-throat aspect ratio, pore, and throat shape factor were computed using the maximal ball algorithm (Dong and Blunt, 2009). These distributions are demonstrated in Fig. 11(d–h). The pore and throat shape factor have been defined in Section 4.1.1. The aspect ratio indicates the ratio of the pore radius to the linked average value of all the throat radii (Wu et al., 2018). As for the pore size distribution, most pore radii (64.18%) are distributed from 8 to 18 μm. Relating to the throat radius distribution, about 73.82% throat radii are constituted between 4 and 12 μm. The pore and throat shape factor distributions
imply that the throats are smoother than the pores because the shape factors of the throats are overall larger than them of the pores. Once more, the most pore and throat shape factors are less than 0.071, which reveals that the pores and throats in the cross sections are not circular, which also proves our statement in Section 4.1.1. When it comes to pore-throat aspect ratio distribution, 92.86% aspect ratio can be found between 2 and 6, and the largest aspect ratio is 44.09.

4.1.5. Comparison of pore size distributions: SEM, MICP, NMR, and X-ray CT

In order to better summarize the advantages and disadvantages of the SEM, MICP, NMR, and X-ray CT experiments in characterizing pore

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**Fig. 6.** NMR relaxation time (T2) distributions of saturated and irreducible saturated five samples from the study area with their total porosity (phi in %) from NMR. Figures (a), (b), (c), (d) and (e) are from S1, S2, S3, S4 and S5, respectively.
systems, pore size distributions obtained from these experiments are compared in Fig. 12. It is evident that NMR and MICP can cover more pore sizes than SEM because the experimental sample size (2.5 cm) of NMR and MICP is much larger than the utilized sample in SEM (about 2 mm). More accurate aperture distributions can be obtained if a larger SEM is available. Apart from this, more features of pores and throats can be attained through SEM images. For example, one can find the micropores and ultra-micropores in clay minerals, measure the pore size and the morphological characteristics. In addition, NMR can obtain more information about smaller pores (less than 0.004 μm) than MICP, because it is easier for water to enter tiny pores of water-wet rocks than mercury. In fact, mercury in MICP test was the non-wetting phase so it cannot go into these very tiny pores even under the maximal pressure.

Table 3

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
</tr>
</thead>
<tbody>
<tr>
<td>n (μm/ms)</td>
<td>0.027</td>
<td>0.0225</td>
<td>0.0318</td>
<td>0.050</td>
<td>1.895</td>
</tr>
</tbody>
</table>

Fig. 7. The cumulative probability curves of the T₂ relaxation time and NMR. When the cumulative probability curve of the T₂ relaxation time is tangent with one of MICP, the coefficient n will be determined. Figures (a), (b), (c), (d) and (e) are from S1, S2, S3, S4 and S5, respectively.
Therefore, the porosity of the same sample from NMR is more than that from MICP. Besides, the pore radii measured by MICP tend to be smaller than NMR and SEM. In fact, the reason is that $P_c$ and $S_h$ measured by MICP refer to the throat radius and the volume of the pores connected by the throat, respectively. In other words, the radius obtained from Eq. (3) is the throat radius, not the pore size. The volume of the injected mercury in the MICP test is the total volume of the throat and the pores. This is pore shielding in the MICP test (Li et al., 2015). The effect of pore shielding leads to uncertainty in pore size distribution from MICP, which generally results in underestimating the aperture distributions. But overall, the pore radius distributions measured by the three methods are similar, especially SEM and NMR. As to NMR, it is a good technique to measure aperture distributions. However, the coefficient between transverse relaxation time ($T_2$) and pore/throat radius ($R$) varies for different samples. It is cumbersome to get the coefficient of every sample. As such, finding a good solution to calculate is necessary. In terms of X-ray CT technique for S5, compared the former three methods, it can measure more pore structure parameters, including the geometry and topology properties such as connectivity, coordination number, and pore and throat shape factor, but also can be used for

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Porosity</th>
<th>Macropores</th>
<th>Porosity</th>
<th>Proportion</th>
<th>Mesopores</th>
<th>Porosity</th>
<th>Proportion</th>
<th>Micropores</th>
<th>Porosity</th>
<th>Proportion</th>
<th>Ultra-micropores</th>
<th>Porosity</th>
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<tbody>
<tr>
<td>S1</td>
<td>12.25</td>
<td>0.06</td>
<td>0.74</td>
<td>0.51</td>
<td>6.25</td>
<td>0.21</td>
<td>2.57</td>
<td>0.22</td>
<td>2.70</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S2</td>
<td>14.82</td>
<td>0.02</td>
<td>0.30</td>
<td>0.42</td>
<td>6.23</td>
<td>0.36</td>
<td>5.34</td>
<td>0.20</td>
<td>2.96</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S3</td>
<td>12.09</td>
<td>0.01</td>
<td>0.12</td>
<td>0.52</td>
<td>6.29</td>
<td>0.23</td>
<td>2.78</td>
<td>0.24</td>
<td>2.90</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S4</td>
<td>15.38</td>
<td>0.07</td>
<td>1.08</td>
<td>0.54</td>
<td>8.30</td>
<td>0.20</td>
<td>3.08</td>
<td>0.19</td>
<td>2.92</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S5</td>
<td>14.03</td>
<td>0.32</td>
<td>4.49</td>
<td>0.49</td>
<td>6.87</td>
<td>0.19</td>
<td>2.66</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 8. Pore size distributions of S1-S5 from NMR experiment.

Fig. 9. Porosity change of subvolume with the volume (voxels).
simulating single-phase and multi-phase flow in the pore system. These advantages of X-ray CT cannot be replaced by other methods. However, the imaging size of the X-ray CT technique is controlled by its resolution, which results in ignoring micro-pores features smaller than the resolution and missing the ones larger than the size of the image. Thus, for rocks with high heterogeneity or fractures, it is difficult to capture the full pore structure details because the sample size of CT scanning is generally small. Therefore, it is necessary to model a multi-scale digital rock which should contain micropores and macropores. One can integrate several digital rocks of different resolutions into one large-scale digital rock (Tahmasebi, 2018c).

4.2. Fractal dimension analysis of pore structure

4.2.1. Methodology

For pores with fractal features, fractal dimensions are used to describe the regularity and fragmentation of the pore space. The relationship between fractal dimension $D_f$ and pore radius $r$ of the pore space is as follows (Ge et al., 2016; Li et al., 2017):

$$N(r) \propto r^{-D_f},$$

(12)

where $N(r)$ is the number of pores of which pore radius is more than $r$. Differentiating Eq. (12), one can obtain the pore radius distribution function $f(r)$,

$$f(r) = \frac{dN(R)}{dr} \propto r^{-D_f-1}.$$

(13)

Assuming that the pore volume of a pore $v$ and its pore radius can be expressed as

$$v \propto r^3.$$

(14)

Thus, the pore accumulative volume of the pore space where the pore radius is more than $r$ can be obtained by:

$$V_r = \int_r^{\infty} f(r)vdr = \int_r^{\infty} ar^{-3-D_f} dr = b(r^{3-D_f} - r^3).$$

(15)

where $r_{\text{max}}$ is the maximum pore radius, $a$ and $b$ are constants and they are related to the shape of the pores. When $r = r_{\text{min}}$, the whole pore volume can be gotten by:

$$V(r_{\text{min}}) = b(r_{\text{max}}^{3-D_f} - r_{\text{min}}^{3-D_f}).$$

(16)

Combining Eqs. (3) and (4), one can obtain the pore volume cumulative frequency $F(>r)$

$$F(>r) = \frac{V(>r)}{V(>r_{\text{min}})} = \frac{(r_{\text{max}}^{3-D_f} - r^{3-D_f})}{(r_{\text{max}}^{3-D_f} - r_{\text{min}}^{3-D_f}).}$$

(17)

Owing to $r_{\text{min}} \ll r_{\text{max}}$, Eq. (6) can be simplified as

$$F(>r) = \left(\frac{r_{\text{max}}^{3-D_f} - r^{3-D_f}}{r_{\text{max}}^{3-D_f}}\right) \approx 1 - \left(\frac{r}{r_{\text{max}}}\right)^{3-D_f}.$$

(18)

Thus, pore volume accumulation frequency $F(<r)$ with pore radius less than $r$

$$F(<r) = 1 - F(>r) = \left(\frac{r}{r_{\text{max}}}\right)^{3-D_f}.$$

(19)

4.2.2. Fractal dimension from MICP

In the MICP experiment, the pore volume cumulative frequency with pore radius less than $r$ can be written as:
The following formula is reasonable,
\[ F(<r) = 1 - S_H(r) \]  
Therefore, the following formula is reasonable,
\[ \log (1 - S_H(r)) = (D_T - 3) \log P - (D_T - 3) \log P_{\min}. \]  

One can determine \( D_T \) based on the slope of the double logarithmic plot with \( \log (1 - S_H(r)) \) and \( \log P \). When we computed the \( D_T \) of these samples, we noticed that the pores with different sizes have fractal characteristics. Thus, we divided the pores into four groups based on...
the fractal dimension and the pore size distributions, as mentioned earlier in Section 4.1.2. The fractal dimensions of macropores ($D_{f1}$), mesopores ($D_{f2}$), micropores ($D_{f3}$) and ultra-micropores ($D_{f4}$) are be computed based on Eq. (21). The fractal dimension $D_f$ of the entire pores will be obtained using the weighted average of $D_{f1}$, $D_{f2}$, $D_{f3}$, and $D_{f4}$ as following:

$$D_f = \frac{D_{f1} \times \phi_1 + D_{f2} \times \phi_2 + D_{f3} \times \phi_3 + D_{f4} \times \phi_4}{\phi}.$$  (22)

In Eq. (22), $\phi_1$, $\phi_2$, $\phi_3$, $\phi_4$, and $\phi$ are the porosity of the macropores, mesopores, micropores, ultra-micropores and all the pores, respectively. Taking the S1 an example, one can get $D_{f1}$, $D_{f2}$, $D_{f3}$, and $D_{f4}$ from Fig. 13. The detailed parameters about the fractal dimension of all the samples are listed in Table 5. It can be clearly seen that the $D_{f1}$, $D_{f2}$, $D_{f3}$, and $D_{f4}$ of the same sample gradually decrease, which indicates that the large pores are more irregular, fragmentized and heterogeneous because $D_{f1}$ is the largest for the same sample. Overall, the surface of the pore space of all of the samples is rough as the fractal dimensions $D_f$ are more than 2.4.

### 4.2.3. Fractal dimension from NMR

Regarding the NMR test, the following equation can be derived from

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**Fig. 12.** Comparison on pore size distributions of S1-S5 from SEM, MICP and NMR.
Eqs. (8) and (19):

\[ \log(F(<r)) = (3 - D_f)\log T_2 - (3 - D_f)\log T_{2\text{max}}. \]  

Eq. (23) is similar to Eq. (21), so one can calculate \( D_f \) for NMR using a similar method described in Section 4.2.1. The schematic diagram of the fractal dimensions of four kinds of pores in S1 are shown in Fig. 14. The fractal dimensions of all the samples from NMR tests are presented in Table 6. As can be seen, the fractal dimension of macropores is relatively large. But, for S1-S4 samples, the fractal dimensions of micropores are greater than the fractal dimensions of mesopores. Furthermore, the fractal dimension of the entire pores for the same sample from NMR experiments is approximate to, but smaller than that from the MICP tests, which may be for the reason that more ultra-micropores can be captured by NMR and these pores smooth the surface of the system.

![Fig. 13. Schematic of determining the fractal dimension of S1 from the MICP test.](image1)

![Fig. 14. Schematic of determining the fractal dimension of S1 from NMR experiment.](image2)

**Table 5**

Fractal dimension parameters of all the samples from the MICP test.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>( D_f )</th>
<th>Macropores</th>
<th>Mesopores</th>
<th>Micropores</th>
<th>Ultra-micropores</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D_{\phi1} )</td>
<td>( \phi_1 )</td>
<td>( D_{\phi2} )</td>
<td>( \phi_2 )</td>
<td>( D_{\phi3} )</td>
<td>( \phi_3 )</td>
</tr>
<tr>
<td>S1</td>
<td>2.60</td>
<td>2.99</td>
<td>0.84</td>
<td>2.56</td>
<td>5.52</td>
</tr>
<tr>
<td>S2</td>
<td>2.61</td>
<td>2.99</td>
<td>0.29</td>
<td>2.89</td>
<td>5.99</td>
</tr>
<tr>
<td>S3</td>
<td>2.68</td>
<td>2.99</td>
<td>0.46</td>
<td>2.66</td>
<td>1.14</td>
</tr>
<tr>
<td>S4</td>
<td>2.68</td>
<td>2.97</td>
<td>0.78</td>
<td>2.61</td>
<td>7.29</td>
</tr>
<tr>
<td>S5</td>
<td>2.62</td>
<td>2.97</td>
<td>2.72</td>
<td>2.51</td>
<td>6.39</td>
</tr>
</tbody>
</table>
4.2.4. Fractal dimension from X-ray CT

As mentioned, the pores from X-ray CT cannot cover all types of pores. Therefore, only the fractal dimensions of the 3D image and 2D images of S5 are computed in the part. The fractal dimension of the 3D image of S5 is analyzed to describe the roughness of the pore surface while $D_f$ of 2D images is calculated to understand the irregularity of pore boundaries in each layer. The less smooth the surface is, the bigger the fractal dimension (Cai et al., 2015; Ge et al., 2016). The fractal dimension of 3D pore systems is 2.45, which reveals the surface of pore space is not smooth. The fractal dimensions of 2D images demonstrated in Fig. 15 are more than 1.3. Moreover, the porosity of each layer Fig. 15 was also calculated to show the heterogeneity of the pore space. The pore space of S5 is heterogeneous because the porosity of each slice fluctuates significantly. Interestingly, the fractal dimension and porosity of each layer have similar variation trend, which can be due to the fact that the high porous layer with large pores tend to has high fractal dimension.

In summary for Section 4.2, the fractal dimensions of all types of pores can be calculated using MICP and NMR techniques. Comparing the fractal dimensions obtained by MICP and NMR, one can discover that the fractal dimension from MICP is larger. As to the X-ray CT method, the fractal dimensions of the 2D and 3D pore systems both are obtained. Moreover, the fractal dimension of the pores and the porosity of each layer in the 2D images show similar variation trend.

5. Conclusion

The geometrical, topological and fractal characteristics of the pore structure of Es4s reservoir from the Shahejie formation in the Wangjiagang field, Dongying depression, Bohai Bay Basin, China were analyzed based on SEM, MICP, NMR, and X-ray CT experiments. Besides, a novel method of calculating pore size based on pore shape factor from 2D images was put forward. According to pore size distributions measured through these techniques, the advantages and disadvantages of SEM, MICP, NMR, and X-ray CT were summarized. NMR and MICP can cover more pores (ultra-micropores, micropores, and macropores) in the rock than SEM and X-ray CT. Nevertheless, the pore size obtained from MICP tends to be smaller than NMR and X-ray CT because the pore shielding exists in the MICP test. In addition, NMR is an effective method to characterize the pore structure. Unfortunately, the coefficient between pore radius and $T_2$ relaxation time is difficult to compute, so it is necessary to find a better method to calculate it. Moreover, X-ray CT is a promising technique that can acquire a large number of geometry and topology properties of the pore system and the digital rock model can also be used to perform the single-phase or multi-phase flow simulation. Whereas, for low-permeability and tight rocks, micro-CT is not enough to fully characterize the pore systems because sub-resolution micropores in the cores cannot be captured. In fact, those micropores have a very crucial influence on the transport properties of the porous media. Therefore, it is indispensable to model the multiscale digital core that should contain large and small pores for complex rocks, which will be significant to analyze pore systems and simulate multi-phase flow in porous media. Furthermore, characterization of the pore systems should also be linked to mineralogical analysis for better analyzing the effects of mineral wettability on the transport of hydrocarbons in such media.

On the other hand, the fractal dimension of pore space was calculated based on MICP, NMR, and X-ray CT tests. MICP and NMR techniques can be used to analyze the fractal dimension all types of pores, from ultra-micropores to macropores. The macropores tend to be more irregular and heterogeneous than ultra-micropores and micropores. The fractal dimension from MICP is larger than one from NMR for the

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>$D_f$</th>
<th>$q_f$</th>
<th>$D_{f2}$</th>
<th>$q_{f2}$</th>
<th>$D_{f3}$</th>
<th>$q_{f3}$</th>
<th>$D_{f4}$</th>
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<td>0.74</td>
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Fig. 15. Change of fractal dimension and porosity of each layer from X-ray CT.
sample. Besides, the fractal dimensions of the 2D and 3D pore space can be obtained from the X-ray CT data. However, the fractal dimension of microporosity and ultra-microporons cannot be obtained by this method because its resolution is low. It can be proved that the fractal dimension of pore space from 2D CT images changes with the area of pore space, so the fractal theory is an efficient tool for classifying pore types and assessing reservoir quality.

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Appendix A. Supplementary data

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References


