Transp Porous Med (2011) 89:533–545
DOI 10.1007/s11242-011-9784-z

Prediction of Microscopic Remaining Oil Distribution Using Fuzzy Comprehensive Evaluation

Jian Hou · Sunkang Zhang · Yanhui Zhang · Rongrong Wang · Fuquan Luo

Received: 20 May 2010 / Accepted: 5 May 2011 / Published online: 26 May 2011

Abstract A network model is established through the techniques of image reconstruction, a thinning algorithm, and pore–throat information extraction with the aid of an industrial microfocus CT scanning system. In order to characterize actual rock pore–throat structure, the established model is modified according to the matching of experimental factors such as porosity, permeability, and the relative permeability curve. On this basis, the impacts of wetting angle, pore radius, shape factor, pore–throat ratio, and coordination number as applied to microscopic remaining oil distribution after water flooding are discussed. For a partially wetting condition, the displacement result of a water-wet pore is somewhat better than that of an oil-wet pore as a whole, and the possibility of any remaining oil is relatively low. Taking the comprehensive effects of various factors into account, a prediction method of remaining oil distribution is presented through the use of fuzzy comprehensive evaluation. It is seen that this method can predict whether there is remaining oil or not in the pore space with satisfactory accuracy, which is above 75%. This method thus provides guidance for a better understanding of the microscopic causes of the remaining oil.

Keywords Network simulation · Water flooding · Remaining oil · Fuzzy comprehensive evaluation · Prediction

1 Introduction

The main blocks in the Eastern China oilfield mostly have entered a high-water-cut stage, and the remaining oil is highly dispersed. Both macroscopic and microscopic heterogeneities are the internal reasons to account for the distribution of remaining oil. Traditional study of percolation is focused mostly on the larger scale pattern (Gao et al. 2005; Song et al. 2006) and consists mostly of descriptions of reservoir macro-heterogeneity. However, research on a

J. Hou (✉) · Y. Zhang · R. Wang · F. Luo
College of Petroleum Engineering, China University of Petroleum, Dongying 257061, China
e-mail: houjian@hdpu.edu.cn

S. Zhang
Research Institute of Geologic Science, Jiangsu Oilfield, Sinopec, Yangzou 225009, China

macro-scale approach does not reveal the physical and chemical properties of porous media, whereas micro-studies can make up for this deficiency (Blunt et al. 2002). Thus, the prediction method of the microscopic remaining oil distribution after water flooding is proposed for learning more about the microscopic percolation mechanisms in combination with microscopic percolation experiments and simulations. It has great significance for the remaining oil potential and for improving developmental response.

Recently, pore-network modeling has been an important method for studying microscopic flow, with a variety of both petroleum and environmental applications. After the first introduction of pore-network modeling (Fatt 1956), many related studies have been completed. Recently, network modeling studies on wettability effects, three-phase flow, capillary-pressure prediction, and macroscopic conductivity were conducted (Dias and Payatakes 1986; Øren and Bakke 2003; Jackson et al. 2003; Suicmez et al. 2008; Tripathi 2009). Meanwhile, the network model has been widely applied to many aspects of oil and gas field development such as non-darcy flow, foam flow in porous media, formation damage, and non-Newtonian fluid flow (Cannella et al. 1988; Sorbie et al. 1989; Siqueira et al. 2003; Perrin et al. 2005; Hou 2007).

To make accurate predictions, it is essential that the networks be topologically representative of the porous medium of interest. Three-dimensional (3-D) images of rock microstructure are the basis for the prediction of rock flow properties. Presently, there are three methods for constructing a data field of 3-D images: nuclear magnetic resonance imaging or X-ray computed tomography (Hazlett 1995; Rigby and Gladden 1996; Arns et al. 2004), stochastic microstructural modeling (Adler and Thovert 1998; Liang et al. 1998; Okabe and Blunt 2004), and process-based simulation of rock-forming processes (Bryant et al. 1993; Bakke and Øren 1997; Jin et al. 2003). Among these methods, the first is the most accurate method that can directly reflect the distribution of pore space.

The aim of this study is to investigate the influence of microscopic reservoir factors on remaining oil distribution using a pore-scale network model. The network is established on the basis of the CT experiment's results from actual cores, and the surface wettability of the pore–throat in the network model is generated by the matching of the core's relative permeability curve. Partially wetting does not just consider a single condition. Because of this, the model is more likely to be truly predictive. At the same time, existing randomness in a study of microscopic remaining oil distribution has its basis in statistics. Thus, this article establishes the prediction method of microscopic remaining oil distribution with the combination of fuzzy comprehensive evaluation, based on the study of the factors influencing the microscope residual oil distribution.

2 Microscopic Simulation

2.1 Construction of a Network Model Based on CT Experiments

This article reports on 2-D slice images that are obtained through CT scanning of rock microscopic pore structure, and then how 3-D data fields are constructed by image reconstruction. On the basis of these data, the method for extracting the distribution of pores and throats, as well as the topology, is proposed by the combination of the thinning algorithm. Thus, the network model is finally constructed (Hou et al. 2008).

The core model is made of natural sand from the Kendong 70-1 well in the Shengli oilfield. The experimental porosity is 34.0%, the absolute permeability is 3.52 μm^2, the diameter is 3 mm, and the length is 5 cm.

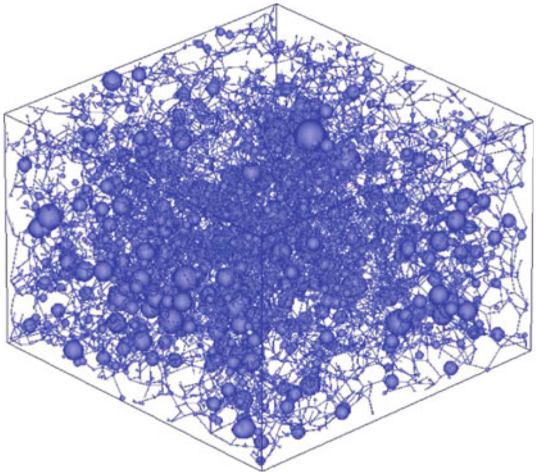

Fig. 1 Network model constructed based on CT experiments

The experiment is conducted using ACTIS-225FFi CT/DR/RTR microfocus CT equipment made by BIR Company of America. In the process of CT scanning, the unsaturated fluid core is scanned. The total scanned length is 1.25 mm, and 100 slices are scanned with a constant distance along the length direction. After image preprocessing, interpolation, and segmentation, the 3-D structure is reconstructed with the combination of the marching cube algorithm (Lorensen and Cline 1987; Hou et al. 2009). Thus, the 3-D visualization is realized.

The thinning algorithm is used for the result of reconstruction order to establish the network model and get the pore–throat structure of the rock core model. On the basis of the pore–throat structure, the features of pores and throats are extracted, and the ultimate network model is shown in Fig. 1. The ball represents pore, and the line represents throat; the sizes of the balls reflect the spatial variations of the pores. The aperture of the line-like throat has the same cross-section shape along its length. However, different throats have different cross-section shapes, and various shapes are simplified as three shape in the model: circle, triangle, and square. The more regular the pore shape is, the greater the shape factor is; and the circle's shape factor is the largest. The size of the network model is $1.78 \times 1.78 \times 1.25$ mm, resulting in 11,602 pores and 15,686 throats. A total of 10,421 pores and 13,939 throats are inside the model, and other elements are at the boundary of the model.

2.2 Network Simulation of Water–Oil Flow

Initially, the network is fully saturated with water and is strongly water-wet. Primary drainage is used to simulate the formation of a reservoir. The wettability in some parts of the network will be changed by the invasion of oil. Imbibition is used to simulate the first water flooding after primary drainage.

Before displacement, the network model is fully saturated with displaced fluid (water). At the beginning of displacement, the displacing fluid (oil) is injected from the entrance. As the pressure of the displacing fluid gradually increases, the displacing fluid enters the network model to displace fluid until the water saturation or capillary pressure reaches a given value. The invasion percolation method (Wilkinson and Willemsen 1983) is adopted at every step during displacement. In particular, units (pore or throat) with the lowest threshold pressure are selected for entrance of the displacing fluid.

Table 1 Network model parameters

Parameter	Value
Size	1.78 × 1.78 × 1.25 mm
Throat number	15686
Pore number	11602
Pore radius	3.0–236.3 μm
Average pore radius	20.4 μm
Throat radius	4.0–52.3 μm
Average throat radius	8.9 μm
Throat length	8.0–322.1 μm
Average pore–throat ratio	2.97
Average coordination number	2.72
Oil viscosity	72.0 mPa s
Clay content	11%
Equilibrium contact angle	35°–150°
Oil–water interfacial force	30 mN/m
Porosity	34.7%
Absolute permeability	3.056 μm^2

For a unit with polygonal section (triangle, square, etc.), part of the water still remains in the corners of the pore after primary drainage, which insure the water in the network can find an exit path. The amount of water in the corners of the pore decreases as the capillary threshold pressure increases until irreducible water saturation is reached. If the pressure increases further, the saturation of each phase changes very little.

After primary drainage, the imbibition process of water flooding is carried out. Due to the change in wettability of some pores, some water remains in the corners. The mechanism of water flooding is much more complex than that of primary drainage. Displacement mechanisms were described at the pore level of water-wet and partial water-wet systems (Lenormand et al. 1983). There are three types of displacement: piston-type, pore body filling, and snap-off displacement.

After constructing the network model based on the rock core from the Kendong 70-l well, microscopic simulation is conducted to match the porosity, absolute permeability, and relative permeability curves. In the process of matching, factors of pore–throat structure and surface property are adjusted. When matching the porosity, relative permeability, we adjust the characteristic parameters of throats and pores (such as the size of pores and throats) proportionally and globally. The wettability of every pore or throat is given by probability distribution function, so the matching of wettability is performed by adjusting the characteristic parameters of probability distribution function. The calculated porosity is 34.7%, and the absolute permeability is 3.056 μm^2. The results are consistent with those of core tests. The constructed network model is partially wetting, and most pores are oil-wet. The parameters of simulation are shown in Table 1.

The matched results of the relative permeability curves are shown in Fig. 2. The scatter points are the calculated results of relative permeability in water flooding of network simulation. The solid lines are the results of laboratory experiments. The calculated irreducible water saturation and the residual oil saturation are 27.3% and 34.1%, respectively. These

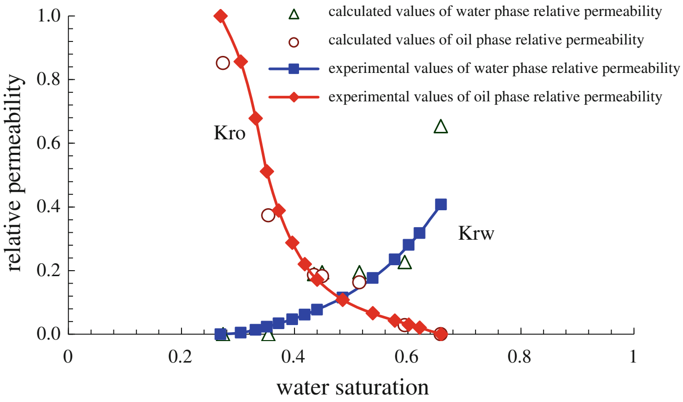

Fig. 2 The matching of relative permeability curves

results are consistent with the results of laboratory experiments in which the irreducible water saturation and the residual oil saturation are 26.8% and 34.5%, respectively. Also, the trends of the curves are consistent.

On the basis of network simulation results of water flooding, the remaining oil distribution statistics of the 3-D network model are conducted at the residual oil stage after water flooding, and then the impact of reservoir factors on the microscopic remaining oil distribution is discussed. Furthermore, the prediction method of the remaining microscopic oil distribution is established in combination with fuzzy comprehensive evaluation.

3 Influence of Characteristic Geometrical Parameters

There are many factors that influence microscopic remaining oil distribution, and the main influential factors are rock-surface property parameters, pore–throat structure, and fluid parameters. The relationship between the influential factors and the microscopic remaining oil distribution is investigated on the basis of the statistical results of the 3-D network simulation.

Wetting angle, pore radius, shape factor, pore–throat ratio, and coordination number represent the surface property, size, shape, and connectivity of pores, respectively. The studies prove that pore wettability is one of the most important influence factors on microscopic remaining oil distribution. Thus, we classify the pores in the network models into water-wet (wetting advancing angle $\leq 90°$) and oil-wet (wetting advancing angle $> 90°$) according to the equilibrium wetting angle. Furthermore, the remaining oil distribution statistics are determined by dividing the values of pore radius, shape factor, pore–throat ratio, and coordination number into different intervals.

In order to discuss the effect of the rock's microscopic factors on the remaining oil distribution, the existing possibility of remaining oil is introduced as the reference index, and it is assumed that pores and throats with water saturation lower than 85% retain the remaining oil. In all intervals of factor distribution, a statistical study is made on the ratio of the remaining oil pores. Actually, the ratio of pores retaining the remaining oil reflects the possibility of the remaining oil in a pore on the effect of only one characteristic geometrical factor. Statistical samples are the pore data of the model at the residual oil stage after water flooding.

Generally speaking, the water-wet pores have better displacement results than oil-wet pores in mixed-wetting rocks. Thus, the possibility of the remaining oil is relatively low in mixed-wetting rocks. Meanwhile, statistical results also show that the statistical distribution of remaining oil for partially wetting is different from that for single-wetting conditions (Li et al. 2005).

3.1 Effect of Pore Radius

Pore radius represents the pore size; Fig. 3a shows these statistical results. For the oil-wet pore, capillary force is resistant for water-driven oil in the process of imbibition and is inversely proportional to the pore radius. The smaller the pore radius, the larger the capillary force is, and the easier it is for oil to remain in the pore than to be driven out, which indicates the increasing the amount of remaining oil in the pore. However, the opposite is true for the water-wet pore.

3.2 Effect of Shape Factor

The shape factor is introduced for quantitatively characterizing the shape of the pore cross section and is defined as:

$$G = \frac{A}{P^2} \tag{1}$$

where A is the cross-section area of a certain element (pore or throat) area of the cross section, and P is the perimeter (Masan and Morrow 1991). The smaller the shape factor, the more irregular the pore shape is. Figure 3b shows these statistical results. For the water-wet pore, the existing possibility of remaining oil increases as the shape factor increases. This is

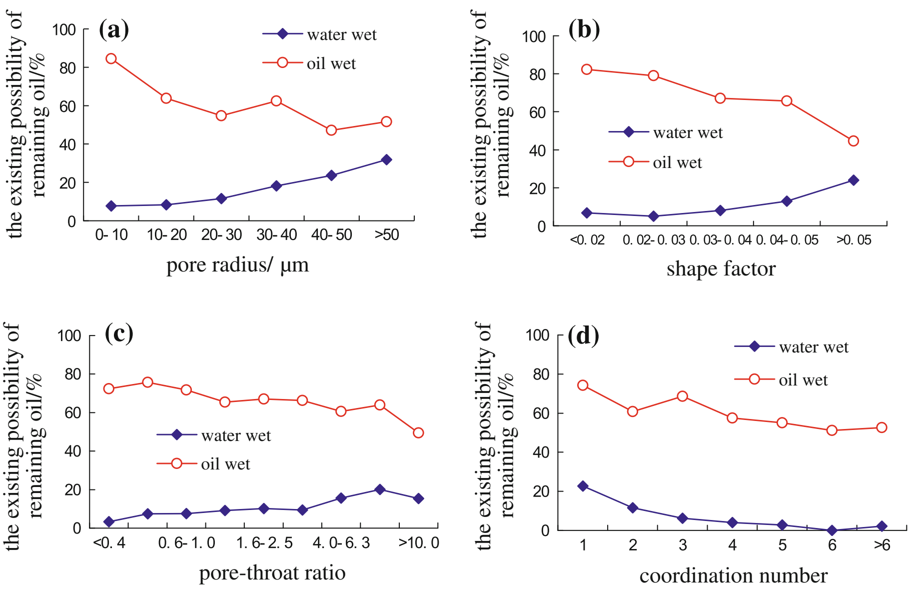

Fig. 3 The effect of influence factors on microscopic remaining oil distribution. **a** pore radius, **b** shape factor, **c** pore–throat ratio, and **d** coordination number

Table 2 The effect degree of influence factors on microscopic remaining oil distribution

Influence factor	Water wetting		Oil wetting	
	Impact factor	Effect degree grade	Impact factor	Effect degree grade
Pore radius	0.0425	2	0.0560	3
Shape factor	0.0306	1	0.0593	3
Pore–throat ratio	0.0434	2	0.0252	1
Coordination number	0.0316	1	0.0404	2

because the smaller the shape factor is, the more irregular the pore shape is, and it is much easier for water to collect in cube corners, lowering the possibility for remaining oil. Whereas for the oil-wet pore, much oil is dispersed in the cube corners, and the possibility for the remaining oil increases in the case of a small shape factor.

3.3 Effect of Pore–Throat Ratio

Pore–throat ratio is defined as the ratio of pore radius and the average throat radius that connects with it. Figure 3c shows these statistical results. For the water-wet pore, the possibility of remaining oil increases as the pore–throat ratio increases. For a pore with a certain radius, an increased pore–throat ratio significantly decreases the average throat radius that connects with the pores, making the accumulation of remaining oil much easier. For the oil-wet pore, the possibility of remaining oil is higher if the smaller pore–throat ratio has a smaller pore radius.

3.4 Effect of Coordination Number

The coordination number represents the connectivity of the pores and is the number of the throat or pore connecting with the pore. Figure 3d shows these statistical results. The possibility of remaining oil decreases as the coordination number increases either for the water-wet pore or the oil-wet pore. This is because the coordination number increases, the oil flow channels increase, and the possibility of remaining oil decreases.

3.5 Varying Influence of the Different Factors

In order to quantitatively characterize varying influence of the different factors on the microscopic remaining oil, a parameter (the impact factor) is defined as:

$$\Omega = \frac{\sqrt{\sum_{i=1}^{m}\left(V_i - \bar{V}\right)^2}}{m} \tag{2}$$

where m is the distribution interval number of the influence factors, V_i is the probability of the remaining pore oil when the influence factors represent a certain internal percentage (%). $\bar{V}$ is the probability of the remaining pore oil in the whole network model as a percentage (%).

The impact factor characterizes the dispersion of a set of data, and the bigger the value of the impact factor is, the larger the difference is between each data set. Table 2 shows the varying influence of different factors on the remaining microscopic oil distribution. The influence factors in the descending order of the effect degree for the water-wet pore are pore–throat ratio, pore radius, coordination number, and shape factor. For the oil-wet pore, the influence factors are shape factor, pore radius, coordination number, and pore–throat ratio. We determine the effect degree grades according to the value of each impact factor. Thus, the bigger the value of the impact factor is, the larger the effect degree grade is.

4 Prediction Method

The fuzzy comprehensive evaluation (Zhang et al. 1992) can create good statistics and fuzzy processing for influence factors and get the remaining oil membership value for each factor to establish the evaluation matrix for fuzzy evaluation. Thus, we get the value of the fuzzy synthetic evaluation and can predict the remaining oil distribution quantitatively.

4.1 Definition of Factor Set

The elements of the factor set are the influence factors of the evaluation objects. If we describe from the n positive respect, the factor set (U) can be defined as:

$$U = \{u_1, u_2, \ldots, u_n\} \tag{3}$$

where $u_i (i = 1, 2, \ldots, n)$ are the influence factors. According to the single-factor evaluation result, the main factors that influence the microscopic remaining oil distribution after water flooding include wettability, pore radius, shape factor, pore–throat ratio, coordination number, etc. At different wetting conditions, the evaluation factor set we established is:

$$U = \{\text{pore radius, shape factor, pore–throat ratio, coordination number}\} \tag{4}$$

4.2 Definition of Comment Set

The comment set can have many elements or even just a single element. The prediction of the microscopic remaining oil is just to decide whether the pore containing residual oil or not. So, we can establish a single-comment set (V):

$$V = \{\text{existing remaining oil in the pore}\} \tag{5}$$

4.3 Definition of Weighting Set

Generally speaking, every influence factor has a different effect degree on the study objective, so we give the factors a weighting to quantitatively describe the effect degree of each influence factor. The distribution of the weighting is a fuzzy subset (A) of the factor set, that is:

$$A = \{a_1, a_2, \ldots, a_n\} \tag{6}$$

In practical applications, a_i is required to meet normalization and non-negative conditions, that is: $\sum_{i=1}^{n} a_i = 1; a_i \geq 0, (i = 1, 2, \ldots, n)$. The value of weighting set A can be obtained according to the effect degree of each factor on the evaluation results with the analytic hierarchy process (AHP), which can objectively and quantitatively characterize the human subjective judgment using a certain scale. AHP is one of a multi-criteria decision-making method that was originally developed by Thomas L. Saaty in 1980.

According to the single factor evaluation result, and the influence of factors on the microscopic remaining oil distribution after water flooding, a comparison between each two factors is made, and then the comparative scale for relative importance can be obtained. We establish

Table 3 Judgment matrix on water-wet condition

Influence factor	Pore radius	Shape factor	Pore–throat ratio	Coordination number	Weighting value
Pore radius	1	2	1	2	0.3333
Shape factor	1/2	1	1/2	1	0.1667
Pore–throat ratio	1	2	1	2	0.3333
Coordination number	1/2	1	1/2	1	0.1667

Table 4 Judgment matrix on oil-wet condition

Influence factor	Pore radius	Shape factor	Pore–throat ratio	Coordination number	Weighting value
Pore radius	1	1	3	3/2	0.3653
Shape factor	1	1	3	3/2	0.3653
Pore–throat ratio	1/3	1/3	1	1/2	0.1278
Coordination number	2/3	2/3	2	1	0.1416

the evaluation matrix shown in Tables 3 and 4 and calculate the weighting set on the water-wet and oil-wet conditions, respectively, according to the 1–9 scale method (Saaty 1980). The results show: $A_1 = \{0.3333, 0.1667, 0.3333, 0.1667\}$ for the water-oil condition and $A_2 = \{0.3653, 0.3653, 0.1278, 0.1416\}$ for the oil-wet condition. After a consistency check, judgment matrix A_1 and A_2 satisfy the consistency requirement.

4.4 Definition of Evaluation Set

The evaluation set can be established as:

$$R = \{R_1, R_2, \ldots, R_n\} \tag{7}$$

where R_i $(i = 1, 2, \ldots, n)$ are the value of single-factor evaluation, which is determined by the membership value of the comment set in the intervals divided by the factor. Taking the value range and the distribution character of each factor into account, the distribution intervals are divided as, respectively:

Pore radius (µm): 0–10, 10–20, 20–30, 30–40, 40–50, >50;
Shape factor: <0.02, 0.02–0.03, 0.03–0.04, 0.04–0.05, >0.05;
Pore–throat ratio: <0.4, 0.4–0.6, 0.6–1.0, 1.0–1.6, 1.6–2.5, 2.5–3.4, 3.4–6.3, 6.3–10.0, >10.0;
Coordination number: 1, 2, 3, 4, 5, 6, >6.

We establish statistics for the possibility of remaining oil in the corresponding distribution interval of each factor in the network model (Fig. 3), and thus we can get the membership value of the remaining oil probability. In our statistical work, it is assumed that pores and throats with water saturation lower than 85% exist for the remaining oil. It is worth noting that we first judge the wettability and then take values in different distribution intervals of each factor on the water-wet or oil-wet condition for each pore.

After getting the membership value of each factor, we can obtain the comprehensive evaluation results of the evaluation objective according to the corresponding weighting matrix $\bar{A}$ and evaluation index system $\bar{R}$, resulting in evaluation matrix $\bar{B}$:

$$\bar{B} = \bar{A} \cdot \bar{R} \tag{8}$$

The comprehensive evaluation model of weighting average is used in this article.

4.5 Illustrative Example

Take pore no. 2 in the network model as an example. The equilibrium wetting angle is 168°, the pore radius is 38.3μm, the shape factor is 0.0625, the pore–throat ratio is 1.66, and the coordination number is 4.

The weighting matrix is $\bar{A} = [0.3653, 0.3653, 0.1278, 0.1416]$ owing to the oil-wet condition, and the evaluation matrix $\bar{R} = [0.6250, 0.4462, 0.6703, 0.5748]^{\mathrm{T}}$ is obtained by taking the membership value of each factor that influences the pore, respectively.

We obtain the comprehensive evaluation result, $\bar{B} = \bar{A} \cdot \bar{R} = [0.5584]$, using the evaluation index system constructed by the membership value of each factor and the evaluation weighting value of the corresponding factor. This value shows that the existing possibility of the remaining oil in pore no. 2 of the network is 55.84% at the residual stage after water flooding.

5 Results

We predict the remaining microscopic oil distribution on the basis of network simulation results with the combination of the fuzzy comprehensive evaluation method for all pores in the network model. The pore is considered to contain remaining oil if the evaluation result is larger than the threshold value of the comprehensive evaluation we defined. Once a threshold value is determined, we can obtain the corresponding number of pores containing remaining oil by statistical methods. Thus, when the threshold value changes from 0 to 1, the relationship curve between the number of pores containing retaining oil and the comprehensive evaluation value can be obtained (Fig. 4). The number of pores containing retaining oil decreases with a corresponding increase in the threshold value of the comprehensive evaluation.

According to network simulation results, the number of pores retaining oil—that is, the pores with water saturation lower than 85%—is 5,971 at the residual stage after water flooding. So, we define the threshold value of comprehensive evaluation as 0.63 according to the relationship curve shown in Fig. 4; that is, taking the comprehensive evaluation result larger

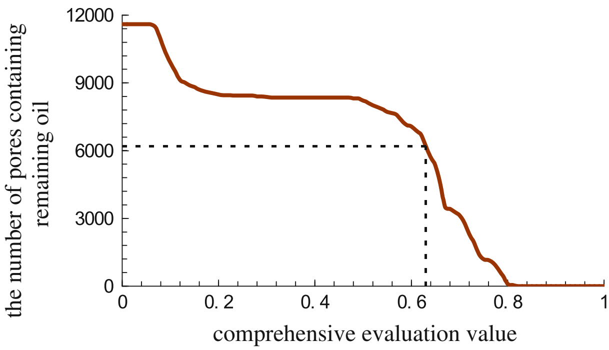

Fig. 4 The relation between the number of pores containing remaining oil and the comprehensive evaluation value

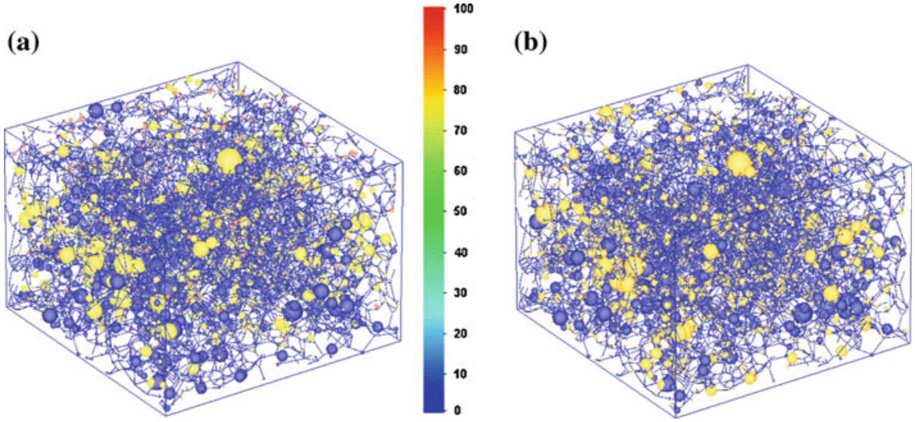

Fig. 5 The result comparison of the microscopic remaining oil distribution in network model. **a** the remaining oil distribution by network simulation and **b** the result of fuzzy comprehensive evaluation

than 0.63 as the judging standard of remaining pore oil. According to this standard, there are 6,190 pores retaining oil in the model, using fuzzy comprehensive evaluation, which is close to the actual simulation result. Further statistical results show 4,554 pores whose water saturation is lower than 85% among the pores retaining oil as determined by fuzzy comprehensive evaluation (the comprehensive evaluation result is greater than 0.63). So, we know that the accuracy of fuzzy comprehensive evaluation is 76.27%.

Figure 5 shows the comparison of remaining oil distribution as the result of network simulation and as that of fuzzy comprehensive evaluation. It can be seen that the trends of distribution are consistent as a whole. Figure 5a is the oil saturation distribution of pores obtained by the network simulation; the color bar represents the degree of oil saturation in the network model. Figure 5b is the result of comprehensive evaluation; the yellow pores show remaining oil, and the blue ones do not. In Fig. 5, the throats are shown in blue and do not reflect remaining oil distribution.

6 Conclusions

(1) On the basis of rock CT scanning, the network model is established through the techniques of image reconstruction and network construction. In order to characterize actual rock pore–throat structure, the established model is modified according to the matching of experimental parameters such as porosity, permeability, and the relative permeability curve.
(2) The wettability of pores is one of the main factors that influence microscopic remaining oil distribution. For mixed-wet rock, the displacement result of the water-wet pore is somewhat better than that of the oil-wet pore as a whole, and the existing possibility of remaining oil is relatively low. Furthermore, pore radius, shape factor, pore–throat ratio, and coordination number also are principal factors that influence microscopic remaining oil distribution.
(3) Taking the comprehensive effects of various factors that influence remaining oil distribution after taking water flooding into account, the prediction method of remaining oil distribution is presented in combination with fuzzy comprehensive evaluation. These

results indicate that the method can predict whether there is remaining oil or not in pores with satisfactory accuracy, which is higher than 75%. The results also provide guidance for understanding some of the reasons for microscopic remaining oil.

Acknowledgments The writers greatly appreciate the financial support of the National Natural Science Foundation of China (Grant No. 10772200, 10972237), the Important National Science & Technology Specific Projects of China (Grant No. 2011ZX05011), China Postdoctoral Science Special Foundation (Grant No. 200902180), and the Fundamental Research Funds for the Central Universities (Grant No. 10CX03002A).

References

Adler, P.M., Thovert, J.F.: Real porous media: local geometry and macroscopic properties. Appl. Mech. Rev. **51**(9), 537–585 (1998)

Arns, C.H., Knackstedt, M.A., Pinczewski, W.V., Martys, N.S.: Virtual permeametry on microtomographic images. J. Pet. Sci. Eng. **45**(1–2), 41–46 (2004)

Bakke, S., Øren, P.E.: 3-D pore-scale modeling of sandstones and flow simulations in the pore networks. SPE J. **2**(2), 136–149 (1997)

Blunt, M.J., Jackson, M.D., Piri, M., Valvatne, P.H.: Detailed physics, predictive capabilities and macroscopic consequences for pore-network models of multiphase flow. Adv. Water Resour. **25**(8-12), 1069–1089 (2002)

Bryant, S.L., Mellor, D.W., Cade, C.A.: Physically representative network models of transport in porous-media. AIChE J. **39**(3), 387–396 (1993)

Cannella, W.J., Huh, C., Seright, S.R.: Prediction of xanthan rheology in porous media. SPE 18089. SPE Annual Technical Conference and Exhibition, Houston, Texas, 2–5 October (1988)

Dias, M., Payatakes, A.: Network models for two-phase flow in porous media, part 1. Immiscible microdisplacement of non-wetting fluids. J. Fluid Mech. **164**, 305–336 (1986)

Fatt, I.: The network model of porous media: I. Capillary pressure characteristics. Trans. AIME **207**(1), 144–159 (1956)

Gao, X., Yu, X., Li, S., Wang, Q., Liang, W.: Forecast of remaining oil distribution by using neural network technology. Acta Pet. Sin. **26**(3), 60–63 (in Chinese) (2005)

Hazlett, R.D.: Simulation of capillary-dominated displacements in microtomographic images of reservoir rocks. Transp. Porous Media **20**(1–2), 21–35 (1995)

Hou, J.: Network modeling of residual oil displacement after polymer flooding. J. Pet. Sci. Eng. **59**(3-4), 321–332 (2007)

Hou, J., Li, Z., Zhang, S., Cao, X., Song, X., Gao, D.: Experiment and simulation study on construction of three-dimensional network model. Sci. China (Ser G) **51**(11), 1761–1774 (2008)

Hou, J., Li, Z., Zhang, S., Cao, X., Du, Q., Song, X.: Computerized tomography study of the microscopic flow mechanism of polymer flooding. Transp. Porous Media **79**(3), 407–418 (2009)

Jackson, M.D., Valvatne, P.H., Blunt, M.J.: Prediction of wettability variation and its impact on flow using pore- to reservoir-scale simulations. J. Pet. Sci. Eng. **39**(3–4), 231–246 (2003)

Jin, G., Patzek, T.W., Silin, D.B.: Physics-based reconstruction of sedimentary rocks. SPE 83587. Proceedings of the SPE Western Regional/AAPG Pacific Section Joint Meeting, Long Beach, California, 19–24 May (2003)

Lenormand, R., Zarcone, C., Sarr, A.: Mechanism of the displacement of one fluid by another in a network of capillary ducts. J. Fluid Mech. **135**, 337–353 (1983)

Li, Z., Hou, J., Cao, X., Chen, Y., Song, X., Wang, K.: Simulation for influence of microscopic reservoir parameters on remaining oil distribution. Acta Pet. Sin. **26**(6), 69–73 (in Chinese) (2005)

Liang, Z.R., Fernandes, C.P., Magnani, F.S., Philippi, P.C.: A reconstruction technique for three-dimensional porous media using image analysis and Fourier transforms. J. Pet. Sci. Eng. **21**(3-4), 273–283 (1998)

Lorensen, W.E., Cline, H.E.: Marching cubes: a high resolution 3D surface construction algorithm. Comput. Graph. **21**(4), 163–169 (1987)

Mason, G., Morrow, N.R.: Capillary behavior of a perfectly wetting liquid in irregular triangular tubes. J. Colloid Interface Sci. **141**(1), 262–274 (1991)

Okabe, H., Blunt, M.J.: Prediction of permeability for porous media reconstructed using multiple-point statistics. Phys. Rev. E **70**, 066135 (2004)

Øren, P.E., Bakke, S.: Reconstruction of Berea sandstone and pore-scale modeling of wettability effects. J. Pet. Sci. Eng. **39**(3-4), 177–199 (2003)

Perrin, C.L., Tardy, P.M.J., Sorbie, K.S., Crawshaw, J.C.: Experimental and modeling study of Newtonian and non-Newtonian fluid flow in pore network micromodels. J. Colloid Interface Sci. **295**(2), 542–550 (2005)

Rigby, S.P., Gladden, L.F.: NMR and fractal modelling studies of transport in porous media. Chem. Eng. Sci. **51**(10), 2263–2272 (1996)

Saaty, T.L.: The Analytic Hierarchy Process. McGraw Hill, New York (1980)

Siqueira, A.G., Bonet,E.J., Shecaira, F.S.: A 3D network model of rock permeability impairment due to suspended particles in injection water. SPE82232. SPE European Formation Damage Conference. The Hague, The Netherlands, 13–14 May (2003)

Song, K., Wu, Y., Ji, B.: A φ-function method for estimating distribution of residual oil saturation in water drive reservoir. Acta Pet. Sin. **27**(3), 91–95 (in Chinese) (2006)

Sorbie, K.S., Clifford, P.J., Jones, E.R.W.: The rheology of pseudoplastic fluids in porous media using network modeling. J. Colloid Interface Sci. **130**(2), 508–534 (1989)

Suicmez, V.S., Piri, M., Blunt, M.J.: Effects of wettability and pore-level displacement on hydrocarbon trapping. Adv. Water Resour. **31**(3), 503–512 (2008)

Tripathi, I.: Pore structure and wettability. PhD. Thesis, University of Houston (2009)

Wilkinson, D., Willemsen, J.F.: Invasion percolation: a new form of percolation theory. J. Phys. A **16**, 3365–3376 (1983)

Zhang, Y., Zou, S., Su, F. : The Method of Fuzzy Mathematics and Application. Coal Industry Press, Beijing (in Chinese) (1992)