Investigation effect of wettability and heterogeneity in water flooding and on microscopic residual oil distribution in tight sandstone cores with NMR technique

Pufu Xiao*, Xiaoyong Leng, Hanmin Xiao, Linghui Sun, Haiqin Zhang, Shisheng Mei, and Hanyu Zhang

Abstract: In order to explore the effect of wettability and pore throat heterogeneity on oil recovery efficiency in porous media, physical simulation experiment and nuclear magnetic resonance (NMR) measurements were conducted to investigate how crude oil residing in different sized pores are recovered by water flooding. Experimental results indicate that the recovery factor of water flooding is governed by spontaneous imbibition and also pore throat heterogeneity. It is found that intermediate wetting cores lead to the highest final recovery factor in comparison with water wet cores and weak oil wet cores, and the recovery oil difference in clay micro pore is mainly because of the wettability, the difference in medium pore and large pore is affected by pore throat heterogeneity. Water wet core has a lower recovery factor in medium and large pore due to its poor heterogeneity, in spite of the spontaneous imbibition effect is very satisfying. Intermediate wetting cores has significant result in different sized pore and throat, the difference in medium pore and large pore is affected by pore throat heterogeneity.

Keywords: CO₂ flood; microscopic displacement mechanism; microscope pore throat structure; tight sandstone reservoirs; nuclear magnetic resonance

1 Introduction

The large amount of unconventional resources, especially tight oil, has attracted more attention in China, recently [1]. However, the great heterogeneity, poor reservoir properties and low pressure may elevate the difficulty of enhanced oil recovery (EOR) in tight oil reservoir [2, 3]. As for such tight formations, primary recovery remains as low as 5.0-10.0% of original oil in place (OOIP), even after long horizontal wells have been drilled and massively fractured [4]. Because of the high capillary pressure and super-low injectivity, the oil production is relatively low [5, 6]. Currently, water flooding is still the most economical way to supplement energy, but because of the lack of understanding the flooding mechanisms, it is usually considered that the recovery efficiency by water flooding is very low if the formation is oil-wet. Meanwhile, the recovery efficiency of water-wet formation is relatively high [7–10]. Wettability is an important petrophysical property, which impacts the rock fluid properties such as relative permeability, capillary pressure and distribution of residual oil. Although some previous papers have studied the effects of wettability on waterflood oil recovery and relative permeability [11, 12], a little attention has been focused on wettability and heterogeneity effect on the fluid flow in the such tight formations and compared the residual oil saturation from different pore throats at a microscopic level during the process of waterflooding, presently. The water flooding recovery in tight oil formations depends critically on the wetting properties of the rock matrix and porosity microstructure character. They both play an important role during the process of water flooding. Therefore, it is critical
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Various methods have been used to investigate the microscopic residual oil distribution, such as the photoetching model, the micro displacement model built with true sandstone, and the X-CT scanning technique, etc. Nuclear magnetic resonance has recently been developed and has become a popular and effective tool of providing realistic assessment of the amount of fluid that can flow in the porous media [13–15]. A distribution of decay times, called transverse relaxation times (T₂), can be used to describe the distance between crude oil and core pore surface. Details of the NMR principles can be found in the following papers.

The major purpose of this study is to elucidate the dependence of residual oil in a microscopic level on the following factors: (1) wettability; (2) microscopic pore throat heterogeneity. In this paper, core samples are obtained from Changqing oilfield in China, we have conducted core-flood tests, NMR test, constant rate mercury intrusion tests, spontaneous imbibition tests, and investigated the injection process, recovery factor (RF) and residual oil saturation distribution under different wettability cores. The distribution of remaining oil in different pore throats was analyzed by the NMR, and elucidate the reason of different residual oil saturation.

2 Experimental set-up and procedures

2.1 Experimental procedure

The oil samples and sandstone core samples are collected from the layer of Chang 8, which located in the southern district of Ordos basin, properties of core samples are listed in Table 1. The experimental apparatus is mainly composed of five parts: injection system, displacement system, production system, pressure control system and data acquisition system (Figure 1). The experimental procedure is briefly described as follows. Firstly, core samples were saturated with simulated brine water under a pressure of 12.00 MPa for 12 h. Then the core samples were placed in the NMR apparatus for testing its transverse relaxation time (T₂) spectrum. Secondly, to eliminate the hydrogen signals of water in the core, the core samples were firstly displaced with Mn²⁺ solution (15000 mg/L). Thirdly, NMR T₂ spectrum was measured after the core was saturated with the oil till the initial oil saturation was achieved. Fourthly, after water flooding, and the NMR T₂ spectrum was measured again at the end of the displacement. Finally, the core slide was placed in the constant-rate mercury injection apparatus to experimentally measure size of the pore and throat. During the experiments, the mercury saturations corresponding to different mercury injection pressures were recorded to infer the pore and throat radius distribution of the core sample.

2.2 Relationship between T₂ response and pore throat radius

The total T₂ response of fluids in porous media can be described with the following equation [16-18],

\[ T_{2,\text{surface}} = \frac{1}{\rho_2 F_s} r_c \]  

Where \( \rho_2 \) is the surface relaxivity (\( \mu m/\text{ms} \)), \( F_s \) is the dimensionless shape factor of a pore, and pore radius, \( r_c \) (\( \mu m \)). When a given core is considered, its surface relaxivity (\( \rho_2 \)) and shape factor (\( F_s \)) can be assumed to be constant. Thus, after obtaining the constant \( \rho_2 \) and \( F_s \), the T₂ spectrum of NMR can be eventually converted into the distribution curve of pore throat radius.

3 Results and discussion

3.1 Pore size distribution and throat size distribution

Figure 2(a) shows the pore distribution for the different wettability core samples with the similar permeability. There exists no large difference in pore size, and the pore exhibits the normal distribution mainly in the 100-150 \( \mu m \). Unlike pore distribution, there is a huge differ-
Table 1: Physical parameters of the core samples

<table>
<thead>
<tr>
<th>No.</th>
<th>Permeability/10^{-3} \mu m^2</th>
<th>Porosity/%</th>
<th>Pore and Throat Type</th>
<th>Wettability type</th>
<th>Injection schemes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>0.415</td>
<td>7.20</td>
<td>Heterogeneity</td>
<td>Weak Oil Wet</td>
<td>Water Flood</td>
</tr>
<tr>
<td>2-2</td>
<td>0.575</td>
<td>15.60</td>
<td>Homogeneity</td>
<td>Intermediate Wet</td>
<td>Water Flood</td>
</tr>
<tr>
<td>3-2</td>
<td>0.583</td>
<td>16.30</td>
<td>Homogeneity</td>
<td>Water Wet</td>
<td>Water Flood</td>
</tr>
<tr>
<td>4-1</td>
<td>0.592</td>
<td>5.40</td>
<td>Heterogeneity</td>
<td>Weak Oil Wet</td>
<td>Brine imbibition</td>
</tr>
<tr>
<td>4-2</td>
<td>0.573</td>
<td>14.40</td>
<td>Homogeneity</td>
<td>Intermediate Wet</td>
<td>Brine imbibition</td>
</tr>
<tr>
<td>4-3</td>
<td>0.564</td>
<td>14.90</td>
<td>Homogeneity</td>
<td>Water Wet</td>
<td>Brine imbibition</td>
</tr>
</tbody>
</table>

Figure 2: (a) Pore radius distribution of different wettability core samples. (b c d) Throat radius distribution of different wettability core samples.

ence in the throat distribution. As seen in Figure 2(b, c, d), the weak oil-wet cores have the narrowest throat distribution, changing from 0.2-0.6 \mu m and the throat peak radius slightly increases along with an increasing permeability. Nevertheless, as for the intermediate wet cores and water wet cores, if the permeability is greater than 0.3 \times 10^{-3} \mu m^2, the peak radius of throat will increase from 0.5 \mu m to 0.6 \mu m. At the same time, the distribution range of throat radius becomes wider obviously, changing from 0.3-2.5 \mu m, 0.2-0.8 \mu m to 0.2-4.2 \mu m, respectively. We can infer that under the same conditions of permeability, the
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3.2 Spontaneous imbibition

Table 2 lists the results of the imbibition experiments. The oil recovery of water wet cores is 26.52%, which is obviously higher than intermediate wet (21.57%) and oil wet core (18.51%). Figure 3(a, b, c) shows pictures of oil droplets on the surface of cores, the wettability make oil droplet easily come out of the water wet core on all sides as brine imbibes, contribute to form relatively small size oil droplet and distributed uniformly. While the intermediate wet core only gets the scattered oil droplet on the top and sides, and these oil droplets are of different size, and the large oil droplet may come from water wet portion. There is almost no visible oil droplet on the sides of weak wet core, and some small oil droplet on the top may result from the buoyancy forces. This suggests that the dominant imbibition mechanism is the counter current imbibition due to the capillary pressure gradient caused by the wettability. Through the analysis of the imbibition process can be more convinced this point. Figure 4 shows the oil recovery as a function of time for the spontaneous imbibition experiments performed. In the first 6 hour, the imbibition rate can be maintain a high value in different wettability cores, in this period the oil in the large pore body appeared on the periphery of the cores. After external oil has been recovered, the recovery rate slowed down for few hours because some deep oil droplet may be blocked in the throat, it only takes 2 hours for water wet core to recover the oil again, and 3 hours, 7 hours for intermediate wet core, weak oil wet core, respectively. 80% of the finally recovered oil is recovered in the first 24 hours, the rate of recovery gradually decreases as the saturation of aqueous phase increases in the core. It is found that the wettability is the key factor for the spontaneous imbibition in tight oil formation.
3.3 T2 Spectrum distributions

As is shown in the Figure 5, $T_2$ distribution curves of saturated water (black curve) can reveal the distribution of pore throats in cores. $T_2$ distribution curves under saturated oil condition (red curve) can reveal the distribution features of pores saturated with oil, and the black section reflects the distribution of irreducible water in pores. $T_2$ distribution curves under residual oil condition (blue curve) can reveal the distribution of residual oil in pores, and the red section reflects distribution of the produced oil in pores. Therefore, study of $T_2$ distribution allows us to analyze and compare the microscopic change of original oil in pore under different injection process. Methodology used to determine the recovery degree of pore throats falling from 0.1 ms – 1000 ms, give the area ($S_{red} + S_{blue}$) stand for the initial oil content contained in different pore throats, and the area $S_{blue}$ stand for the residual oil, the following formula is used to determine the recovery degree in different pore throats.

$$ R = \frac{S_{red}}{S_{red} + S_{blue}} \times 100\% $$  \hspace{1cm} (2)

There is certain corresponding alternate relation between $T_2$ distribution and pore throat distribution in the sandstone sample [19–21]. The relaxation time of $T_2$ are converted into pore radius using the modified linear relation through the Equation 1. Pore throats with radius (< 1µm) would correspond to the size of clay micro pore, while pore throats with radius more than (>10 µm) belong to the large pore, the medium pore is between them (1-10 µm).

3.4 Analysis of residual oil distribution

The measured NMR amplitude distribution as a function of pore size under various conditions for the core samples are plotted in Figure 6. On the whole, the intermediate wet core yield a favorable recovery factor (46.68%) compared the water wet core (36.70%) and weak oil wet core (38.22%). During the water flood process, in spite of the capillary pressure of homogeneity cores is higher than heterogeneity cores due to the lower throat radius, but there is a large proportion of clay micro pore compared to large and medium pore, it makes water to be displaced in the micro pore slowly and evenly. On the contrary, the heterogeneity cores have higher throat radius, and because of the relatively small resistance force in large pores and throats, the water enter into the medium pores and large pores more easily, than clay micro pores. It is interesting to note that, the water wet cores give the worst RF by water flooding and leave the maximum residual oil in the medium pore and large pore. On the one hand, when wetting phase water enter into the medium and large pore, crude oil is pushed off from the pore surface and form the dispersed oil droplets, during the migration of fluid the oil droplets may be entrapped in the smaller throat, resulting from Jamin effect, and cannot form a continuous pathway to flow out. On the other hand, we already know wet cores have a satisfying result from spontaneous imbibition experiment, and the water imbibes into the surrounding dead-end zone replacing the crude oil, thus water wet cores yield the highest RF in the clay micro pore. In this way, the oil is entrapped and stays in medium and large pores as residual oil, thus the overall recovery will be much lower than expected. When it comes to #2-2, although the existence of poor heterogeneity, the intermediate wet cores not only displace most oil in the medium pore and large pore, but also can have favorable RF in the clay micro pore. It is found the water flooding recovery oil difference in clay micro pore is mainly because of the wettability, the difference in medium pore and large pore is affected by pore throat heterogeneity.

4 Conclusions

Through the constant-rate mercury injection method, it is found from core samples with the similar permeability, average pore size is in a range of 100-150 µm and pore throat radius of homogeneity cores is 0.2-0.6 µm, heterogeneity cores throat radius rang 0.2-4.2 µm. By employing the core flood and NMR relaxometry measurements, we investigated how crude oil residing in different sized
Table 2: Spontaneous imbibition results for different wettability cores

<table>
<thead>
<tr>
<th>No.</th>
<th>Length /cm</th>
<th>Diameter /cm</th>
<th>Permeability /$10^{-3}$µm²</th>
<th>Porosity /%</th>
<th>Wettability type</th>
<th>Oil Recovery /%</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-1</td>
<td>5.427</td>
<td>2.491</td>
<td>0.592</td>
<td>9.40</td>
<td>Weak Oil Wet</td>
<td>18.51</td>
</tr>
<tr>
<td>4-2</td>
<td>5.393</td>
<td>2.482</td>
<td>0.573</td>
<td>14.40</td>
<td>Intermediate Wet</td>
<td>21.57</td>
</tr>
<tr>
<td>4-3</td>
<td>5.396</td>
<td>2.484</td>
<td>0.564</td>
<td>14.90</td>
<td>Water Wet</td>
<td>26.52</td>
</tr>
</tbody>
</table>

Table 3: Comparison of Recovery Degrees for Different Scenarios

<table>
<thead>
<tr>
<th>No.</th>
<th>Exp. condition</th>
<th>Recovery factor distribution /%</th>
<th>Oil saturation /%</th>
<th>Recovery factor /%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>&lt;0.5µm 0.5-1µm 1-10µm &gt;10µm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-2</td>
<td>Water Flood</td>
<td>73.05 62.90 31.38 80.77</td>
<td>84.49</td>
<td>38.22</td>
</tr>
<tr>
<td>2-2</td>
<td>Water Flood</td>
<td>54.70 43.44 44.30 73.34</td>
<td>73.62</td>
<td>46.68</td>
</tr>
<tr>
<td>3-2</td>
<td>Water Flood</td>
<td>66.42 45.31 32.05 38.24</td>
<td>67.49</td>
<td>36.70</td>
</tr>
</tbody>
</table>

Figure 6: Distribution of pore size for different cores under different conditions

pore is recovered with wettability and heterogeneity cores, and quantify the recovery factors and residual oil distribution in different sized pores. In the water flooding scenario, water flooding efficiency for the experimental cores varies from 36.70% to 46.68%. The water wet core has a lower recovery factor in medium and large pores due to its poor heterogeneity, in spite of the spontaneous imbibition effect is much satisfying. In comparison, the intermediate wet core has significant result in different sized pores. Oil wet core has made a piston-like displacement in clay micro pores leading to recovery factor of 38.22%.

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References


