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Characteristics of oil distributions in forced and spontaneous imbibition of tight oil reservoir

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ABSTRACT

Matrix imbibition, which includes spontaneous imbibition (SI) and forced imbibition (FI), is the main mechanism of water-based methods, and can play a significant role in unlocking tight oil potentials as a tremendous amount of oil remains in the matrix following primary production. Previously, SI and FI have been investigated separately in pore-scale studies for several years. However, it is difficult for the results to provide guidance for selecting water-based methods owing to the different core samples and pore classification criteria adopted. Therefore, an integrated study of SI and FI is conducted on tight cores in order to understand the characteristics of oil contributions from different pores. In this work, 68 tight cores from the Chang 8 formation, Ordos Basin (China) are investigated. Nine cores are used to test native wettabilities; then, rate-controlled porosimetry is conducted on a typical tight core. Finally, nuclear magnetic resonance is implemented to determine the oil distributions before and after SI and FI for six cores. Based on the petrophysical properties, the cores are classified into three permeability levels (0.06 mD, 0.1 mD, and 0.22 mD). The SI and FI results demonstrate that FI can always provide more than twice the oil recovery factor of SI in each permeability level. For FI, more than 40% of the produced oil is contributed by mesopores. With increasing permeability, macropores contribute more oil than micropores. For SI, the oil contribution from micropores can reach 53.34%. The permeability of 0.1 mD is a critical point at which the oil contribution of mesopores surpasses that of micropores.

1. Introduction

The total recoverable tight oil (including shale oil [1]) available in the world is estimated as 2513×10^8 t, constituting approximately 56.8% of the world's unconventional oil resources [2]. With the assistance of horizontal drilling and multi-stage hydraulic fracturing, the exploitation of tight oil has become profitable [1,3–9]. As with all resource development processes, problems may accompany the benefits. Issues such as a low recovery factor and high production decline rate have resulted in tremendous amounts of tight oil remaining in the matrix following primary recovery [10]. However, tight oil may play a game-changing role if feasible improved oil recovery (IOR) methods are applied to unlock the matrix resources.

As a type of IOR method, water-based techniques have been discussed and partially validated in the field, and awareness of the mechanisms of these methods in unconventional reservoirs [11–15] has been increasing. For tight oil reservoirs, cyclic water injection (CWI) and waterflooding are two methods that have been investigated in both laboratories and fields [4,13,16,17]. The results of these studies indicate that the success of such methods is highly dependent on the efficiency of the matrix imbibition process. Matrix imbibition can be categorized as spontaneous imbibition (SI) or forced imbibition (FI), depending on whether water is imbibed by the capillary pressure alone or with an extra force. SI and FI play different roles in CWI and waterflooding, respectively. It is suggested that SI dominates the displacement process in CWI, while FI forms the primary driving mechanism in waterflooding [4,17,18].

The combination of nuclear magnetic resonance (NMR) and mercury injection methods is a generally accepted approach to investigating the characteristics of oil distributions in SI and FI for tight oil reservoirs at the pore-scale level. For SI, Yang et al. [19] studied the SI characteristics in tight cores (2.1 mD core), considering the effects of mineralogy, pore connectivity, and pore size distribution. Their results indicated that macropores (pore radius > 50 nm) were responsible for the majority of the oil recovery in SI. In their research, the pore classification followed the guidelines proposed by the International Union of Pure and Applied Chemistry (IUPAC), which defines the radius ranges of macropores, mesopores, and micropores as > 50 nm,

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2–50 nm, and < 2 nm, respectively [20,21]. Lai et al. [22] examined the SI fluid flow in both gas/water/rock and oil/water/rock systems on 42 tight cores with the assistance of NMR. They summarized four pore size distribution types in the oil/water/rock system and noted that the wettability and pore structure significantly influence the relaxation time (T_2) distributions. For FI, Yang et al. [23] quantitatively analyzed the residual oil distribution in four water-wet tight cores in waterflooding processes with different constant injection pressures. They found that 41 to 88% of the recovered oil was contributed from pores with radii between 10 and 100 μm. Liu et al. [24] compared the oil contributions from different pores in waterflooding, polymer flooding, and surfactant-polymer flooding processes with the same constant injection rate of 0.1 mL/min. The experimental results of waterflooding indicated that both medium (2–10 μm) and large pores (> 10 μm) play significant roles in oil recovery. The core samples in the aforementioned studies not only had different permeability ranges but were also discussed under different pore classifications. It is difficult to compare the results of these studies directly for understanding the effects of SI and FI on oil recovery contributions from different pores. Therefore, it is important to conduct a systematic study on FI and SI in tight reservoirs in order to understand the mechanisms behind the different water-based methods, as well as to provide guidance for selecting these for a specific reservoir.

In this study, tests are first carried out to measure the petrophysical properties, including porosity, permeability, wettability, and core dimensions. Secondly, constant mercury injection is used to examine the pore size distributions for supporting the NMR interpretation. Finally, NMR measurements are conducted before and after SI and FI. It is worth noting that a constant water injection rate is applied in all FI tests. The oil contributions from different pores can be obtained by means of a comparison of the NMR results between SI and FI. It is significantly useful to select an appropriate water-based method for enhancing tight oil recovery.

2. Background

The target area is known as Shui Mogou, located 90 km northeast of Fu Xian county in Ordos Basin, China. The reservoir contains 1,095,400 t of technically recoverable tight oil. The eighth member of the Triassic Yanchang formation (Chang 8) forms the main layer of the Shui Mogou area. Further information on Chang 8 in this area is summarized in Table 1.

Since 2009, Shui Mogou has received economic oil flow and the average oil rate per well during the first production week was 1.5 t/day. However, the oil production rate continued to decline rapidly. At present, the average oil rate per well has decreased to 0.4 t/day. Therefore, Shui Mogou was selected for studying the oil contribution mechanisms of SI and FI in order to guide the oil company further in the design of a water-based method.

3. Experiments

3.1. Experimental setup

The major experimental setup includes a porosimetry examination, Amott cells, a core-flooding system, and NMR spectrometer. The ASPE-730 automated system is used for rate-controlled porosimetry (RCP). The pump injection rate can be lowered to 0.00006 mL/min to reach a volume resolution of 0.000001 mL. Aided by a precise pressure transducer, the pressure measurement accuracy is 0.05% of the full scale. Amott cells (Vindum Engineering Inc., USA) are used for the imbibition tests, with the minimum volume increment of the Amott cell being 0.1 mL. The core flooding system is applied for core flooding processes. An NMR spectrometer, produced by Peking University, applies UNIQ-PMR the rock sample analyzer. The magnetic field strength is 0.2305 T and the resonance frequency is 10 MHz for ^{1}H. Other devices used in this study include a core milling machine (Xintai Runlian Machinery Equipment Co. Ltd., CN), core cleaner (Hai'an Petroleum Research Instrument Co. Ltd., CN), oven, core measurement system (Hai'an Petroleum Research Instrument Co. Ltd., CN), and analytical electronic balance.

Table 1
Basic information of Shui Mogou area in Ordos Basin.

Properties	Value
Depth of middle Chang 8 formation, m (ft)	1300–1500 (4265–4921)
Average reservoir temperature, °C (°F)	54 (129.2)
Initial reservoir pressure, MPa (Psi)	10.4–12.0 (1508.4–1740.5)
Average reservoir pressure, MPa (Psi)	11.3 (1638.9)

3.2. Fluids

The synthetic oil is mixed by degassed crude oil from the Shui Mogou area and kerosene with a volume ratio of 1:2. At the average reservoir temperature (54 °C), the synthetic oil density and viscosity are 0.816 g/mL and 2.75 mPa.s, respectively, which are identical to those of crude oil.

The reservoir water is sampled from the same wells as those from which the entire cores were collected. The reservoir water analysis data are listed in Table 2. In order to eliminate the ion composition difference between the sources and potential contaminations, formation water is prepared in the laboratory, based on the average reservoir water properties. The formation water properties are also indicated in Table 2. Prior to being used, the synthetic formation water is filtered through a 0.45 μm millipore membrane filter [24,25].

3.3. Cores

The cores are collected from the Shui Mogou area of the Yanchang oil field (Ordos Basin, China). Three typical wells, located in the eastern (Well YL24), middle (Well YL36), and western (Well YL33) parts of the Shui Mogou area, respectively, are selected for core drilling. The core samples, which mainly consist of feldspathic sandstone and debris-feldspathic sandstone [27–29], are obtained from the Chang 8 formation from 1495.5 to 1610.6 m.

In order to understand the core properties of the Chang 8 formation in the Shui Mogou area, the entire cores are firstly drilled with a TX-2 core milling machine to generate long cores with a diameter of 2.52 cm. Secondly, the core samples are cleaned using a toluene-ethanol solution with a volume ratio of 3:1 in a DV-IV core cleaner for five days, and dried in an oven at a temperature of 105 °C for several days [19,30], until the core weight is stabilized. Thirdly, the basic petrophysical properties of the cores are measured once they have cooled to room temperature (21 °C).

Fig. 1 illustrates the porosities and permeabilities of all 68 tight cores. The average porosity and permeability are 8.74% and 0.13 mD, respectively. Fig. 1a indicates that the core porosities are distributed around the average porosity. However, the core permeabilities can obviously be divided into three levels, namely 0.22 mD, 0.10 mD, and 0.06 mD, as illustrated in Fig. 1b.

Based on the classified permeability levels, three long cores from each well are used for conducting the wettability tests, the properties of which are displayed in Table 3. Thereafter, one third of the nine cores in the wettability tests are selected and cut into short cores in order to investigate the effects of SI and FI on oil distributions by means of RCP and NMR tests. The basic data of these short cores are listed in Table 4. It is worth noting that the cores are restored to native wettability by following the recommendations of Gant et al. [25], with the exception of the RCP test.