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The visual and quantitative study of remaining oil micro-occurrence caused by spontaneous imbibition in extra-low permeability sandstone using computed tomography

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ABSTRACT

Spontaneous capillary imbibition plays a significant role in oil displacement mechanism during water flooding operation in extra-low permeability sandstone reservoirs. However, after long-term of waterflooding, most of the oil blobs still remain within the pore space. In this context, quantitative assessment of the micro-occurrence of remaining oil in pore space is indispensable to conduct for an efficient waterflooding operation. In this work, the core sample with 3 mm × 10 mm dimensions was prepared from the southeast area of Ordos Basin Chang6 extra-low permeability formation. Subsequently, high-resolution X-rays CT scanning technology was employed to visualize the changes in fluid distribution during spontaneous imbibition process. By means of image segmentation and three-dimensional (3-D) image reconstruction technique, the images of the remaining oil in the 3-D pore space were obtained. After that, the shape factor and relative volume factor were used to quantify the micro-occurrence of remaining oil in the 3-D pore space. The experimental results show that the total volume of oil was declined to $2.27 \times 10^7\,\mu m^3$ from $4.25 \times 10^7\,\mu m^3$ after spontaneous imbibition in the core sample. Consequently, the continuous oil phase was disrupted by the water in pore space and segmented oil blocks were appeared. Meanwhile, the number of oil blocks was increased to 6027 from 958 that led to severe Jamin's effect and spontaneous imbibition was resultantly came to an end. While in 3-D pore space, three different kinds of micro-occurrences of remaining oil were spotted, such as network (54.31%), cluster (35.28%), and isolated (10.51%). The network and cluster type of remaining oil micro-occurrences are considered as dominant types owing to the large volume and better communication. Because of abrupt capillary force reduction in suddenly enlarge channel and multiple Jamin's effects, the network and cluster remaining oil would mainly be confined in large channels (over than peak pore radius). Therefore, our work provides some beneficial understanding of the remaining oil micro-occurrence in pore space after imbibition.

1. Introduction

The sustainable development of extra-low permeability reservoirs plays a significance to meet the growing demand for oil resources [1,2]. For the last several decades, waterflooding in extra-low sandstone permeability reservoir is mainly applied to increase the depleted inherent energy of reservoir [3–5]. During water flooding operation, the injected water could spontaneously imbibe into the porous media and will assist to displace the remaining oil under the action of strong capillary force [6,7]. However, after long-term of waterflooding, over 80% of the oil would still be left within the pore space. This problem compels the researchers to think about the efficient water injection in extra-low permeability reservoirs [8]. Since spontaneous capillary imbibition plays an important role in water flooding operation in low permeability sandstone reservoirs [9]. Tremendous researches have been conducted on imbibition in core samples that may provide a fundamental concept in current research work [10–13]. According to their research results, not only petrophysical characteristics (wettability, permeability, rock size), but also fluid properties (oil-water viscosity, interfacial tension) could strongly influence the ultimate oil

Abbreviations: CT, computed tomography; 2-D, two dimensional; 3-D, three dimensional; EOR, enhanced oil recovery; KI, Potassium Iodide

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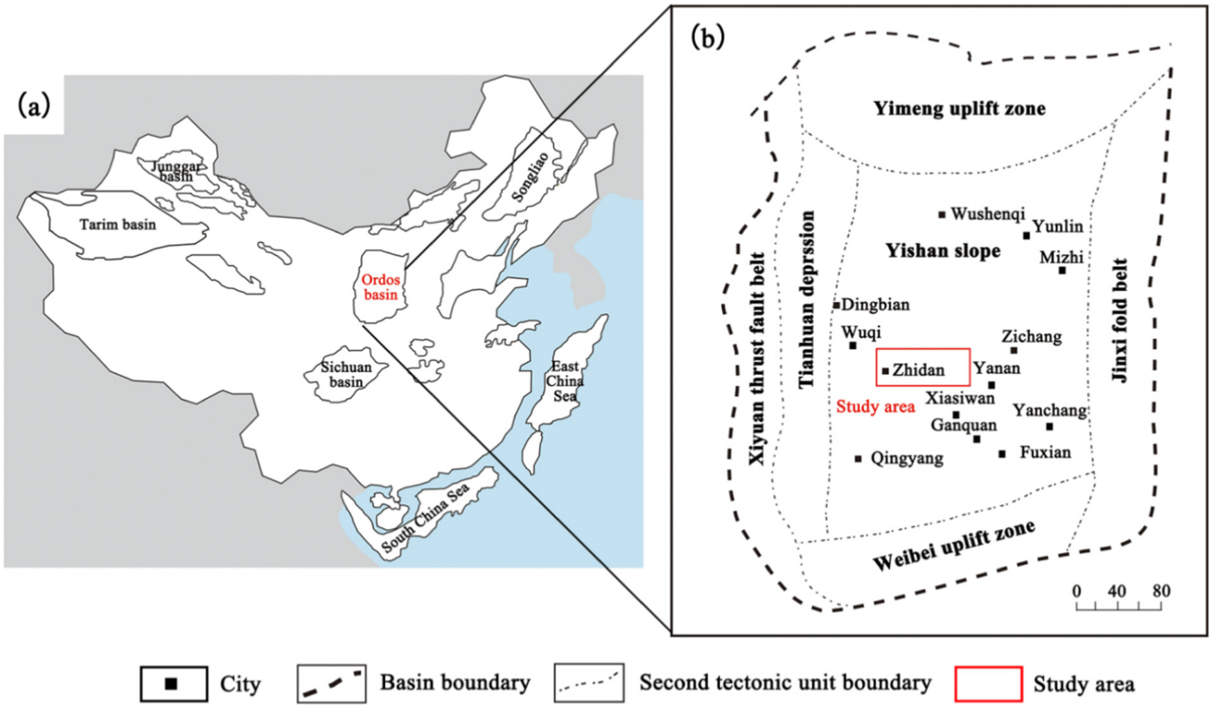

Fig. 1. (a) Ordos Basin, China location. (b) Ordos Basin structural unit map and the study area location [27].

recovery. Furthermore, they have concluded that initially water imbibed sharply and meanwhile the oil saturation decreases in the core sample. After that, the imbibition rate would be plugged to zero. Despite enormous researches on core samples, the microscopic mechanisms behind the imbibition process were not be clearly demonstrated. Therefore, it is necessary to further insight into imbibition mechanism and the micro-occurrence of remaining oil in extra-low permeability reservoir. In this context, compared to other characterization technologies, such as Etched glass model, and NMR, the micro-CT is the most prominent to look into the micro-imbibition process [14,15].

Due to high-resolution visualization and quantitative characterization, the CT scanning technique makes it possible to investigate the three-dimensional (3-D) pore structure characteristics and micro-fluid flow behavior in porous media [16,17]. Mark E. Curtis et al. [18] analyzed the microstructure of different kinds of shale formation using nanometer-scale resolution imaging. According to their result, although pores with a smaller radius (3 to 6 nm) are prevalent in number, but cannot mainly contribute to the total pore-volume. Fujie Jiang et al. [19] characterized the Late Triassic Chang7 member in the Ordos Basin, China by using nanometer-scale resolution X-rays computed tomography. They concluded that organic matter (OM) pore are more conductive to the natural gas diffusion in the high-mature sample, but in mature sample OM pores provided the least connectivity for the natural gas. While over-mature sample falls in between the two where OM pores are intermediately connected to provide a channel for natural gas. Furthermore, based on the understanding of the pore structure, several researchers have used CT to investigate the mechanism of imbibition in porous media and their work has been arranged in chronological order. In 2012, Arief Setiawan et al. [20]. attempted to visually demonstrate the 3-D imbibition process. In addition, they concluded that oil is trapped within pore space due to capillary force. Morteza Akbarabadi et al. [21]. conducted an experiment on shale core sample in 2014. According to their research, brine could not be imbibed in very small diameter pore. However, oil that is trapped in larger pore space can easily be recovered as a result of brine imbibition. After two years, surfactant imbibition in oil-wet fracture rock was studied by Mohammad Mirzaeid et al. [22]. According to their outcomes, surfactant molecule can successfully decrease the capillary force and then imbibition would entirely rely on gravity. In 2017, Morteza Akbarabadi et al. [23]. has categorized pore surface into three type of shale core samples, such as water-wet, oil-wet, and partially-wet. Meanwhile, Mehdi Shabaninejad et al. [24]. showed that, after low salinity brine imbibition, asphaltene films became thinner and were not uniformly distributed on the surface of the rock. Currently, J.O. Alvarez et al. [25]. had used surfactants (anionic-nonionic) solution in shale sample for the purpose of changing the wettability. Furthermore, they also analyzed the influence of wettability alteration to spontaneous imbibition recovery. So far, researchers have used CT scanning technology to further expound the wettability characteristics at the pore scale and also analyzed the mechanism behind the improvement in imbibition by applying either surfactant or low salinity brine. In our previous study, we observed that pore connectivity in tight sandstone samples plays an essential role in oil recovery via spontaneous imbibition process [26]. However, to the best of our knowledge, very limited literature is currently available on the micro-occurrence of remaining oil after spontaneous imbibition, particularly in extra-low permeability sandstone pore space.

In this paper, the core sample with 3 mm × 10 mm dimensions was prepared from southeast area of Ordos Basin Chang6 extra-low permeability formation and the high-resolution X-rays CT scanning technology was employed to visualize the changes in fluid distribution after imbibition process. By means of image segmentation and 3-D image reconstruction technique, the images of the remaining oil in 3-D pore space were obtained. After that, the shape factor and relative volume factor were used to quantify the micro-occurrence of remaining oil in the 3-D pore space. As a consequence, our work provides a strong foundation to further insight into micro-occurrence of remaining oil in pore space.

2. Geological setting

The Ordos Basin (area, 320 000 km^2) is located in the northwest of the China Plate which is actually north-trending giant syncline that has gradual depression towards the east but has dramatic ascent in the west