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Experimental study of boundary condition effects on spontaneous imbibition in tight sandstones

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ABSTRACT

The main objectives of this study were to investigate the effects of boundary condition and pore size on spontaneous imbibition in tight sandstones, and to simulate and interpret the flow process. In this study, scanning electron microscopy (SEM), mercury injection capillary porosimetry (MICP) and nuclear magnetic resonance (NMR) T_2 were combined to investigate the pore systems of the tight sandstone outcrop from Yanchang formation, Ordos Basin. Five parallel sets of imbibition experiments were also carried out, respectively using NMR and imbibition cell to guarantee the reliability of recovery data. Furthermore, a study was conducted to validate the linear model of recovery versus the square root of time in tight sandstones under different boundary conditions. The radial countercurrent flow encounters the linear flow, and causes mutual interference in the late stage of imbibition, which is probably the main reason for a lower recovery of all-face-open (AFO) imbibition than two-ends-closed (TEC) imbibition. Imbibition efficiency decreased with the increase in pore radii around the immovable peak, while it increased with increasing pore radii around the movable peak. The linear relationship between the imbibition recovery and the square root of time was best fitted by TEC imbibition, whereas the relationship in two-ends-open (TEO) imbibition is poor. In addition, different behaviors between TEO imbibition and the other four types indicate that gravity cocurrent flow dominates in the former one.

1. Introduction

Previous studies on fractured porous media have shed light on the importance of imbibition in petroleum reservoirs [1–3]. With advances in hydraulic fracturing techniques, the development of tight oil reservoirs is considered as a crucial method to overcome the depletion of conventional reservoirs [4,5]. However, due to micronano pores and complex pore structure in tight formation, the effect of imbibition on tight oil development is non-negligible. Therefore, a deeper understanding of imbibition mechanisms in tight oil reservoirs with multi-fracture networks is essential for successful exploitation. The expulsion of oil within the matrix by water imbibition is governed by the combined effect of two sets of forces; (a) gravity forces due to the difference in densities between oil and water, and (b) capillary forces due to the interaction of surface forces within the pores [6]. In addition, the performance of imbibition is depended on various factors, such as fluid viscosity, wettability, boundary condition, permeability and porosity, rock type, initial water saturation, matrix length and shape, interfacial tension, among which one hot topic is the effect of boundary condition on imbibition [7]. The dependence of imbibition recovery on boundary conditions and pore size triggers experimental studies of imbibition tests under core-scale conditions.

In previous references, experimental method is the most common one to study various items of imbibition, including (1) the volume method [8], (2) the weighing method [9], (3) the 1D glass tube [10], and (4) the 2D micro-model [11]. The volume method and the weighing method are two conventional methods to quantify oil production by imbibition. The imbibition front versus time can be recorded using 1D glass tube and imbibed oil volume can also be measured. Since the pore structure of rock is complex, the 2D micro-model are also used to visualize fluid movement for imbibition at the pore scale [11]. Recently more and more advanced techniques, are also introduced to observe fluid distribution for imbibition from the medical field, such as NMR and the X-ray CT scanning [12,13].

Core-scale imbibition experiments with various boundary conditions were conducted to simulate the complex oil–water-rock contact relationship under subsurface condition. The boundary conditions used in previous experimental studies mainly include AFO, One-end-open (OEO), TEO, TEO-free, TEC, and partially covered with water [14–18]. Yildiz [14], Zhang [15], and Pooladi-Darvish [16] considered that

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Table 1
Physical properties of outcrop samples for experiments.

Sample	Porosity %	Permeability mD	Length mm	Boundary condition	Apparatus	Oil saturation %
L2	12.5	0.5	50.8	OECU	NMR	95.3
L3	10.2	0.42	50.9	OECD	NMR	89.6
L4	12.2	0.37	50.8	TEC	NMR	95.6
L5	12.0	0.5	50.9	TEO	NMR	94.9
L11	12.3	0.45	50.4	AFO	NMR	96.01
A2	11.6	0.43	50.8	OECU	Imbibition cell	94.3
A3	11.8	0.52	50.9	OECD	Imbibition cell	96.2
A4	12.1	0.47	50.7	TEC	Imbibition cell	93.7
A5	12.3	0.46	50.9	TEO	Imbibition cell	94.5
A11	11.7	0.5	50.4	AFO	Imbibition cell	93.2

three-dimensional countercurrent flow occurs in the AFO system and concluded that OEO is the "worst case scenario" in terms of oil recovery. Cocurrent and countercurrent flows occur in spontaneous imbibition under TEO boundary condition. Even a brine suction was symmetrical, and oil production was often asymmetrical [12,17,19]. The experimental results reported by Yu under TEO showed a higher oil recovery was observed in the top end since both countercurrent and cocurrent flows took place at the top, while only countercurrent flow occurs at the bottom end. Gravity was regarded as an important factor for cocurrent flow [19]. 96% of total recovery was produced cocurrently from the end face (contacted with oil), whereas countercurrent only occurs at the other end (exposed to brine) in "TEO-free spontaneous imbibition" [20]. Bourbiaux also verified this and observed a desaturation front with a smooth slope in the cocurrent flow, whereas the countercurrent flow at earlier time was characterized by a very diffuse and extended front [21]. Pooladi-Darvish reported that cocurrent imbibition dominates oil recovery when a matrix sample is partially covered with water. Previous studies provide insights into the flow modes of spontaneous imbibition under various boundary conditions [16].

In most previous studies, countercurrent experiments showed a clearly lower imbibition rate than that of cocurrent experiments [15,22,23]. However, Zhou et al. [24] observed that the countercurrent flow imbibition rate was faster than that of cocurrent imbibition rate at the early time, and more residual oil was trapped in the former flow mode. In addition, Standnes [22] observed that the ultimate recovery was significantly higher for tests performed under cocurrent flow condition than that under countercurrent flow condition, while Zhang [15] concluded that the ultimate recovery of two flow modes eventually reached the same value. As water and oil flow through the same face in opposite directions, Bourbiaux [21] suggested that the low rates in countercurrent imbibition were caused by the extra viscous resistance of two phases when passing through each other. Arabjamaloei [25] tried to explain this phenomenon from a microscopic perspective. Water spontaneously enters a smaller pore throat, while oil exits from a bigger pore throat and expelled out. They suggested that the capillary pressure of a throat (acting as the resistant force) from which oil is expelled decreases the rate of water expulsion. Akin [8] also observed that countercurrent flow is sensitive to heterogeneity, leaving more residual oil in pores. The conclusion that relative permeability in countercurrent imbibition is smaller than that in concurrent imbibition tests also confirms the fact that the latter is more efficient than the former.

What's more, capillary force is always considered as the main source for spontaneous imbibition recovery. The linear relationship between the recovery by spontaneous imbibition and the square root of time has been proposed by Washburn at first [26]. It was noted by Handy that the model should ignore the effect of gravity [27]. Then lots of imbibition experiments were conducted, processors applied the model when the recovery by spontaneous imbibition or imbibed volume was plotted against the square root of time and found it worked [24,28–31]. According to the reviewed literatures, ignoring gravity seems to make sense at the laboratory because plugs usually tested are small size. However, with the more and more important effect of gravity on imbibition efficiency under various boundary conditions, the application of the model on imbibition experiments under different boundary condition was rarely discussed.

Despite the long history of spontaneous imbibition research, few studies are focused on the reasons causing a recovery difference under different boundary conditions, and most imbibition mechanisms are limited to conventional sandstones, Berea sandstones and dolomite rocks [16–18]. Recently, some attempts have been made to study imbibition in shales and tight sandstones [32–35]. However, tight sandstones have a wide pore-size distribution, complex cracks and nanopores, which are different from conventional rocks [36,37]. Techniques such as CT and NMR, provide new information to facilitate the evaluation of the proposed imbibition mechanism of porous media [38,39].

The work in this study aimed to evaluate the recovery problem under different boundary conditions in tight oil reservoirs. The pore throat structure of tight outcrop sandstones was first investigated using SEM, X-ray, MICP and NMR. Spontaneous imbibition was conducted under five types of boundary conditions using NMR tests. Based on these results, the effects of pore size distribution and boundary conditions on imbibition were discussed, and the performance of recovery was also evaluated. In addition, the application of linear relationship of recovery versus the square root of time to tight sandstones was tested.

2. Experimental section

2.1. Samples and fluids

2.1.1. Samples

Ten tight sandstone plugs were cut from the same outcrops of Ordos Basin, China. The porosity of the target samples was measured by a helium porosimetry and sample permeability was estimated using the pulse-decay technique (Table 1). As ten outcrop samples were cut from the same outcrop, it was assumed that they have uniform permeability and porosity. A PANalytical diffractometer was used to acquire the relative mineral percentage, estimated by a semi-quantitative method. It was performed on powdered tight sandstone at room temperature (20 °C) under a relative humidity (RH) of 66%. For the names of minerals in Table 2, refer to Whitney and Evans [40]. TCCM represents the total content of clay minerals. Table 2 shows that quartz accounts for the highest mineral content with a value of 39.3%, followed by feldspar at 26.9%. The content of kaolinite clay minerals predominating in clay is 76%, whereas illite–smectite mixed layers and illite in clay have mean values of 9% and 15%, respectively.

2.1.2. Fluids

White oil-5 was selected as the non-wetting phase, which is characterized by a density of 0.82 g/cm^3 and a viscosity of 3.5 mPa·s. White oil-5 is a refined mineral oil containing saturated alkanes and is almost