International Journal of Multiphase Flow 93 (2017) 205–212

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmulflow

Mechanical study of the effect of fractional-wettability on multiphase fluid flow

Yukai Qi[a,c,*], Xiaorong Luo[b], Yi Wang[a], Naigui Liu[b], Bo Zhou[a], Jianzhao Yan[d], Likuan Zhang[b]

[a] Research Institute of Petroleum Exploration and Production, Sinopec, Beijing, China, 100083
[b] Key Laboratory of Petroleum Resources Research, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China, 100029
[c] China University of Petroleum (Beijing), Beijing, China, 102249
[d] Chengde Petroleum College, Chengde, China, 067000

ARTICLE INFO

Article history:
Received 29 December 2016
Revised 19 March 2017
Accepted 19 March 2017
Available online 30 March 2017

ABSTRACT

Fractional wettability has been widely recognized in most of the oil reservoirs and it is a crucial factor that controls the fluid flow behavior in porous medium. The overall effect of the proportion of oil-wet grains on the fluid flow properties has been well discussed. However, recent studies found that the random distribution and coordination of oil-wet and water-wet grains could make multi-phase flow behaviors extremely complicated in such media. The multiphase flow mechanisms in fractional wettability media remains unclear. In this study, oil imbibition experiments were systematically conducted using glass cylinders packed with fractional-wet glass beads. To study the effect of fractional wettability on multiple-phase flow properties, samples with different oil-wet grain proportions were prepared, and fifteen repeated experiments were conducted for each oil-wet proportion. The experimental results showed that oil imbibition was largely dependent on but not strictly a function of the proportion of oil-wet grains in the medium. The imbibition behaviors of samples with the same fractional proportion could vary significantly, as some samples exhibited complete oil migration, while others did not. This probabilistic phenomenon is likely due to the random distribution of oil-wet and water-wet grains. A pore throat may behave as oil-wet or water-wet depending on the relative proportion of oil-wet grains the pore throat contains. When the grains that comprise the pore throat are dominated by oil-wet grains, the throat behaves as oil-wet, and vice versa. Only when these oil-wet pore throats are connected to form a complete oil-wet pathway throughout the medium can the oil continuously imbibe into the medium. Therefore, the extent of oil imbibition depends on the completeness of the oil-wet pathway, which is controlled by the proportion of oil-wet grains in the medium. The higher the proportion of oil-wet grains in the medium, the larger the number of oil-wet pore throats that can form; thus, the higher the possibility that those oil-wet pore throats can connect to form continuous oil-wet pathways.

1. Introduction

Wettability is a major factor that controls the effectiveness of flow and displacement when oil and water coexist in a reservoir. Understanding the wettability is critical for predicting residual oil and water distributions in oil reservoirs, as well as for determining development plans and oil recovery strategies (Anderson, 1986, 1987a, b; Schembre et al., 2006).

The internal surface of a reservoir rock is mainly composed of minerals with different surface chemistries and adsorption properties (Anderson, 1986; Barclay and Worden, 2000). As a result, the polar compounds in crude oil can only be adsorbed in certain areas of a rock rendering them oil-wet, while the rest of the rock remains water-wet. (Kovscek et al., 1993; Robin et al., 1995). The heterogeneous wettability of reservoir rock is called fractional wettability (Brown and Fatt, 1956; Salathiel, 1973), which is a widely accepted characteristic of most oil reservoirs (Cuiec, 1991; Kumar et al., 2008; Robin et al., 1995).

The effect of fractional wettability on multi-phase flow behavior has been studied previously (Bradford and Leij, 1995; Fatt and Klikoff, 1959; Lombard and Lenormand, 1993; Morrow, 1976). Initially, researches mainly focused on the effect of the proportion of oil-wet grains on multiphase flow properties. Studies found that the increase in fractional oil wettability decreased the capillary pressure, which lowered the injection pressure required for oil to

* Corresponding author.
E-mail address: y.qi.10@aberdeen.ac.uk (Y. Qi).

http://dx.doi.org/10.1016/j.ijmultiphaseflow.2017.03.016
0301-9322/

displace water (Bradford and Leij, 1995; Fatt and Klikoff, 1959; Lombard and Lenormand, 1993; Hwang et al., 2006). Oil was even observed to imbibe spontaneously into rocks without any additional driving forces (Tong et al., 2003; Zhou et al., 2000).

However, a recent study demonstrated irregular experiment results which may not fit the rules discussed above. Qi et al. (2015) conducted a series of oil imbibition experiments in fully water-saturated fractional-wet media with different proportions of oil wetting glass beads. In the sample with 50% oil-wet grains, the oil imbibed spontaneously from the bottom to the top, while in the sample with 60% oil-wet grains, the oil could not displace the water, and no imbibition occurred. When the proportion of oil-wet grains increased to above 70%, oil imbibition occurred again. They explained this experimental result by referencing previous studies on the distribution and coordination relationship between grains with different wetting properties (Lombard and Lenormand, 1993; Ustohal et al., 1998; Takeuchi et al., 2014; Al-Raoush, 2009).

Ustohal et al. (1998) indicated that the random distribution of grains with different wetting properties in a fractional wetting medium could form many capillary tubes with different wetting angles, which created tortuosity in the fluid flow path. Van Dijke et al. (2001a, b) also noticed that the entry pressures for a fluid not only vary with pore size, but also vary with the oil-water wettability of the pore, thus would greatly affect the filling order of pores. Takeuchi et al. (2014) further noted that for an objective capillary tube to be occupied by fluid in a fractional wetting medium, it must be connected to the fluid pool via other tubes that meet the required wetting conditions. Based on this concept, they proposed a physically based conceptual model to simulate flow properties in a fractional wetting medium. Their computational results showed that the fluid intrusion patterns of samples with different levels of hydrophobic grain mixing but different wetting cell distributions varied significantly.

Therefore, Qi et al. (2015) speculated the irregular experiment results were resulted from the probabilistic distributions of oil-wet and water-wet grains. In the sample with 60% oil-wet grains, the water-wet grains coincidently formed several water-wet barriers near the oil-water contact. These barriers prevented the oil from being connected to the oil-wet pore throats. As the non-wetting phase, the oil could not overcome the capillary pressure in the water-wet pore throats; thus, no imbibition occurred.

Although their theory is logical, it has not been experimentally verified. The mechanism of oil intrusion and the factors that control the extent of intrusion remain unclear. However, their speculations provided possible solution ideas that the probabilistic phenomenon should be verified by statistical methods. Therefore, oil imbibition experiments were systematically conducted to understand the multiphase flow mechanisms in fractional wettability media in this study. The effects of random grain distributions on multiphase flow were observed and discussed based on repeated experiments using 15 samples with the same fractional oil wettability.

2. Experiment

2.1. Measurement principle

In the experiment, The Magnetic Resonance Imaging (MRI) method was used to measure the oil saturations in each sample. The MRI technique has been applied to measure the oil and water saturation by detecting H^+ density since 1990s (Baldwin and Yamanashi, 1989; Chen et al., 1992; Chang et al., 1993; Yan et al., 2012). The observed magnetic intensity depends on the H^+ density the fluid contains. Therefore, the grey value of the obtained MRI image is in direct proportion of the proton density (Edelstein et al., 1988; Chen et al., 1992). If a calibration is carried out aside with a known oil saturation, the oil saturation of the probed sample could then be acquired (Yan et al., 2012).

However, when oil and water coexist in the porous medium, both of the two fluids could generate MRI signals which need to be distinguished. One efficient way is to add Mn^{2+} in the water phase. Under addition of water-soluble Mn^{2+} in water, the relaxation time of H^+ in water molecule will become even shorter, while that in oil remains unchanged (Chang et al., 1993). Under such conditions, it is possible to isolate the MRI signal of oil and neglect the one of the manganese water solution. Oil saturation is measured by comparing MRI signal intensity of the probed sample with the calibration sample:

$$S = \frac{\mathrm{M}}{M'} * S' \tag{1}$$

in which, S and S' are the oil saturation of the probed sample and the calibration sample respectively, M and M' are the observed magnetic intensity of the probed sample and the calibration sample respectively. Fig. 1 shows an example of the processed MRI results of two samples with different oil saturations. Compared with the calibration sample which is fully oil saturated (Fig. 1A), the probed sample shows weaker MRI signals with oil saturation of 75.3% (Fig. 1B).

Detailed principles and image processing methods are described in our previous work (Yan et al., 2012). The average relative error between the direct measurements and MRI derived measurements is only 1.57%, indicating a very good reliability of the MRI method for calculating oil saturation.

2.2. Materials

Glass beads with a uniform size distribution of 0.4–0.6 mm were used as the material in the porous medium. The glass beads were first washed with acidic and alkaline solutions and then heated to 500 °C for 30 min to ensure that they were water-wet. Some of the dried glass beads were then treated using silane to make them oil-wet. The details of this procedure were described by Lombard et al. (1992). The glass beads were placed in a glass cylinder with an internal diameter of 25 mm and height of 200 mm.

The water phase used in this study was deionized water added with $MnCl_2$ with a viscosity of 1.0013 mPa s and density of 1.00635 g/cm^3. The oil phase used in the experiment was kerosene with a viscosity of 1.698 mPa s and density of 0.79161 g/cm^3. The interfacial tension between oil and water was 28.9 mN/m. The kerosene was dyed blue so that its migration within the medium could be easily identified.

2.3. Experimental Procedures

The experimental procedures designed in this study are described as follows.

First, the oil-wet and water-wet glass beads were mixed and stirred evenly. They were then slowly filled into a glass cylinder which is closed at one end and such that the cylinder is not circular. The cylinder was continuously vibrated during the filling process to ensure tight packing. The overall weight of the glass beads was 35 g. We confirmed that the volume associated with this weight of glass beads occupied less than one-third of the glass cylinder to ensure that sufficient kerosene could be imbibed by the porous medium.

Second, a rubber plug was used to put pressure on the glass beads. A 15–18 mm diameter hole was drilled in the rubber plug, and a filter mesh was placed between the beads and the plug (Fig. 2). The rubber plug stabilized the glass beads during experiments, and the filter mesh allowed the oil to remain in direct contact with the glass beads.