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Investigation of the microscopic displacement mechanisms and macroscopic behavior of alkaline flooding at different wettability conditions in shaly glass micromodels

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ABSTRACT

Among various chemical methods, alkaline flooding has a great potential for enhancing heavy oil recovery, especially for reservoirs which contain acidic crude oil. However, fundamental understanding about microscopic displacement mechanisms and macroscopic behavior during alkaline floods at different wettabilities is not well understood, especially in five-spot shaly models. In this work several alkaline floods are performed on a glass micromodel containing randomly distributed shale streaks at different wettability conditions. Various mechanisms responsible for enhancing heavy oil recovery during alkaline flooding are investigated at different wettability conditions. These mechanisms include IFT reduction, deformation of residual oil, pore wall transportation, inter-pore and intra-pore bridging of oil and alkaline solution, the flow of long thin oil strings, production of W/O emulsion at the front, formation of high non-uniform pressure gradient, production of O/W emulsion in the swept regions that leads to emulsification and entrainment and emulsification and entrapment, and wettability reversal (from oil-wet to water-wet and water-wet to oil-wet). The macroscopic investigation of the experiments shows that alkaline injection improves sweep efficiency via formation of W/O emulsion at the front. It also modifies the fingering pattern so that the displacing fluid penetrates and sweeps the oil from around and between the shales. It lingers the breakthrough and reduces the amount of bypassed oil so that a considerable increase in oil recovery factor is observed.

1. Introduction

The need for finding improved methods of oil production is amply illustrated by the large volume of oil considered economically unrecoverable by existing production practice. Water flooding has long been an excellent method of secondary recovery. However, even in those areas of a formation which are well swept by a water flood, 20% or more of the oil remains trapped within the formation and is not recovered. The trapping of oil within the pores of the rock structure results primarily from interfacial forces. If these interfacial forces were altered, it is possible that the trapped oil could be released and recovered.

The oil displacement by alkaline water flooding is one of the techniques in enhanced oil recovery (EOR). The injected caustic solution will react with various natural organic acids occurring in the crude oil to produce surfactant in-situ, which leads to complicated interfacial phenomena and consequently various displacement mechanisms. In order to identify where and when this EOR method is beneficial, it is necessary to study the involved mechanisms comprehensively. In addition, the more appropriate mathematical descriptions and predictions of fluid behavior in porous media rely to a great extent on direct observations. Therefore, attention must be paid to the study of the physical-chemical flow through porous media, especially that of its micro-mechanisms (Guo et al., 1986).

Various mechanisms responsible for increased oil recovery by means of alkaline flooding have been reported by a number of investigators. The mechanisms reported by Jennings et al. (1974) include the reduction of IFT, emulsification of crude oil in-situ that tends to lower injected water mobility, damp the tendency toward viscous fingering, slow water channeling caused by reservoir stratification, and improve volumetric conformance or sweep efficiency. Cooke et al. (1974) stated that IFT reduction, wettability reversal towards oil-wet, emulsification and entrapment, and generation of non-uniform pressure gradient are responsible for improved displacement efficiency of alkaline flooding over ordinary water-flood efficiencies. Johnson (1976) mentioned four fundamentally different

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mechanisms by which caustic can operate. These include (1) emulsification and entrainment, (2) wettability reversal (oil-wet to water-wet), (3) wettability reversal (water-wet to oil-wet), and (4) emulsification and entrapment. Dong et al. (2007) revealed two mechanisms which govern the EOR process during alkaline floods. One is a novel mechanism, in-situ W/O emulsion and partial wettability alteration. The W/O emulsion formed in the injection of alkaline solution blocks the high permeability zones and the pore walls are altered to partially oil-wet, leading to an increase in pressure drop and high tertiary oil recovery. The other mechanism is formation of an O/W emulsion in which heavy oil is emulsified in brine and then entrained in the water phase and produced out of the model.

Several authors discussed the situations under which each type of emulsion is produced (Cooke et al., 1974; Johnson, 1976; Mayer et al., 1983; Srisuriyachai, 2008; Sheng, 2011; Ge et al., 2012; Pei et al., 2013). All of them agree that the production of emulsions mainly depends on the water/oil IFT. The lower the IFT, the easier the emulsions generated. In addition the results of their studies indicate that the conditions for emulsification and entrainment to occur are high pH, low acid number, low salinity, low alkali concentration, and O/W emulsion size lower than pore-throat diameter. The emulsification and entrapment mechanism occurs at high pH, moderate acid number, low salinity, low alkali concentration, and O/W emulsion size bigger than pore-throat diameter. The conditions for generation of W/O emulsion include high alkaline water salinity and high alkali concentration.

Sheng (2011) declared that in chemical flooding, the type of emulsion also depends on the water/oil ratio (WOR). Generally, W/O emulsions are formed at low WOR. As the water cut in emulsions increases, the W/O emulsion type will be transferred to the O/W type. In other words, when one phase volume is much larger, this phase will be continuous. Therefore, the WOR can change the emulsion type. The water cut at which a W/O emulsion is transferred to an O/W emulsion is called the type transferring point or critical water cut. He added that the emulsions formed by water/crude oil or alkali/crude oil are generally the W/O type if the water cut is less than 50% and the O/W type if the water cut is higher than 50%.

Cooke et al. (1974) and Johnson (1976) provided a detailed discussion on the mechanism of W/O emulsion. They stated that the mechanics of the process involve first the conversion of water-wet rock to oil-wet. Here, a discontinuous, non-wetting residual oil is converted to a continuous wetting phase, providing a flow path for what otherwise would be trapped oil. At the same time, low IFT induces formation of an oil-external emulsion of water droplets in the continuous, wetting oil phase. In addition, Sheng (2011) indicated that rock wettability has an influence over which type of emulsion will form in the reservoir. In an oil-wet porous medium, forming W/O emulsion is easy. In a continuous heavy oil system, due to high oil viscosity, water droplets collide less frequently than oil droplets in a less viscous water phase. For this reason, W/O is much more common than O/W emulsion in heavy oil systems.

Several authors (deZabala et al., 1982; Ramakrishnan and Wasan, 1983; Sharma and Yen, 1983; Tong et al., 1986) focused on quantifying the alkaline flooding technique by constructing a chemical displacement model. They implemented this purpose by establishing a relationship between IFT and the essential chemical properties of the acidic oil and the flood-water.

Despite the extensive studies performed on alkaline flooding of conventional oil resources including numerous laboratory experiments and some field tests, the investigations on heavy oil reservoirs are limited due to the adverse mobility ratio between the water and oil phases.

Among various features that influence the performance of alkaline flooding, reservoir wettability has a great importance. Wettability significantly affects the fluids' distribution in medium, fluids' relative permeability, the dominant capillary and viscous forces at pore-scale, the amount of residual oil and irreducible water saturation, and the principal mechanisms responsible for fluid flow in porous network. Nonetheless, the pore-scale distribution of the alkaline solution and oil phase during and at the end of alkaline flooding in a porous medium, and the dominant mechanisms by which alkaline solution displaces the oil phase at different wettabilities, have not been fully understood.

During the late 1980s and the early 1990s, numerous experimental studies examined the role of wettability in various aspects of oil recovery in water flooding (Anderson, 1987; Yadav et al., 1987; Buckley and Morrow, 1990; Morrow, 1990; Yunan and Idris, 1990; Jia et al., 1991; Jadhunandan and Morrow, 1995).

Alkaline flooding is also greatly affected by porous medium wettability, since different displacement mechanisms and therefore diverse recovery factors are obtained at different wettability conditions. Wagner and Leach (1959) and Ehrlich et al. (1974) used high-pH chemicals to show that increasing the water wetness increases ultimate oil recovery. On the other hand, Cooke et al. (1974) reported improved oil recovery with increased oil wetness. Other data show that oil recovery is a maximum when the wettability of a permeable medium is neither strongly water-wet nor oil-wet (Lorenz et al., 1974).

Permeability barriers embedded in the porous medium are frequently the main gross inhomogeneity in many reservoirs which are often referred to as stochastic shales (Begg and Chang, 1985). Obviously, effective single phase permeability of the reservoir decreases due to the presence of discontinuous shales via increasing the tortuosity of fluid flow paths (Jackson and Muggeridge, 1999). Begg and Chang (1985) stated that shale streaks may have some important influences on various reservoir phenomena such as gas/water coning, viscous, capillary or gravitational cross flow, advancement of WOC/GOC, the amount of primary recovery, gravity drainage, and secondary and tertiary EOR operations.

Micromodels are transparent artificial models of porous media that can be used to simulate transport processes at the pore scale (Wilson, 1994). They are produced with the objective of directly observing fluid flow through porous media. Numerous studies have been performed using glass micromodels. They have been used to study specific aspects related to flow in porous media such as wettability (Laroche et al., 1999; Grattoni and Dawe, 2003), capillary pressure (Smith et al., 2005), interfacial tension (Mackay et al., 1998), heterogeneity (Bahralolom et al., 1998), multiple contact miscibility (Campbell and Orr, 1985; Dastyari et al., 2005), water alternating gas injection (Sohrabi et al., 2004), solvent injection (Dehghan et al., 2010; Farzaneh et al., 2010), and gravity drainage (Chatzis et al., 1988; Bora et al., 1997; Mashayekhizadeh et al., 2011).

This study which is carried out by use of a glass micromodel contains two main parts. In the first part a comprehensive study is done on alkaline displacement mechanisms which correspond to the heavy oil production from oil- and water-wet models. This goal is achieved by taking and analyzing microscopic images during and at the end of each experiment. The second part of this study is dedicated to the quantitative evaluation of alkaline flooding at macroscale in a porous medium including randomly distributed shale layers. The effect of shale streaks on the macroscopic behavior during alkaline injection has remained a topic of discussion. Three major subjects are investigated in the second part: (1) the breakthrough time and oil recovery factor of secondary water and tertiary alkaline flooding, (2) the influences of shale layers of random distribution on macroscopic behavior and the amount of trapped oil during water and alkaline flooding, and (3) the effect of wettability on the performance and oil recovery of water and alkaline flooding.

2. Experimental setup

2.1. Experimental apparatus

The provided micromodel setup is composed of a micromodel holder placed on a platform, a high-resolution camera equipped with