Fuel 184 (2016) 826–835

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Visual investigation of the effects of clay minerals on enhancement of oil recovery by low salinity water flooding

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HIGHLIGHTS

- The artificial clayey porous medium was made.
- Initial water-wet and mixed-wet conditions were established.
- Migration of high and low cation-exchange-capacity (CEC) clays were measured.
- Oil recovery using pixel analysis technique was calculated.

ARTICLE INFO

Article history:
Received 4 November 2015
Received in revised form 16 July 2016
Accepted 19 July 2016

Keywords:
Low-salinity water flooding (LSWF)
Oil recovery enhancement
Clay minerals
Fines migration
Initial wettability
Rock–crude oil interaction

ABSTRACT

Experimental study of Low-Salinity Water flooding (LSWF) in sandstone cores by core flooding indicated the presence of fine particles of clay minerals in the effluent. Also, migration of clay particles is considered as one of the major mechanisms for improving oil recovery by LSWF. In addition, it is believed that the presence of clay minerals is one of the necessary conditions for a positive impact of LSWF because clay/crude interaction plays an essential role in the initial wettability of porous media. However, a clear role of clay minerals in this process has not been identified. The aim of this study is to investigate oil recovery enhancement by fines migration at micromodel scale during LSWF. To this end, kaolinite and sodium bentonite were utilized as migratory and swelling clays in the glass micromodel to create clayey porous media. The results indicated that when the porous medium lacked clay minerals, LSWF did not enhance oil recovery. In the clay-coated porous medium that was free of connate water, the crude oil was adsorbed on the pore surfaces, and under this condition, LSWF caused the migration of clay particles with clinging oil droplets due to the electrical double layer force, which improved oil recovery and water wetness. If the porous medium contained clay minerals and connate water, the crude oil did not stick on the pore surfaces. Hence, in both seawater flooding and LSWF, film-flow was observed, which meant that migration of fines by LSWF did not contribute to the oil recovery enhancement. Our work showed that LSWF would be effective as the secondary recovery method if polar compounds of crude oil were adsorbed on the pore surfaces, which means that the initial wettability of porous media must be mixed-wet. LSWF in the clay-coated porous media with high cation-exchange-capacity clay in the primary mode increased the interstitial velocity in some pore paths due to pore-plugging by swelling of clay and finally led to sectional sweeping.

1. Introduction

Low-salinity water flooding (LSWF) is an eco-friendly and economical method of enhanced oil recovery (EOR) as it does not need toxic and expensive materials [1]. It is generally accepted that LSWF increases the oil recovery, but more research is still needed to reach a comprehensive understanding of the mechanism(s) behind this incremental recovery. More than 17 different hypotheses for LSW effects have been proposed, of which the most notable are fines migration, an increase of pH and reduction of interfacial tension (IFT) like in alkaline flooding, multicomponent ionic exchange (MIE), the salt-in effect, osmotic pressure, and electrical double layer (EDL) effects. Although there is no consensus on this issue, desorption of the crude oil component from the pore walls and subsequent wettability alteration towards water-wetting is

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http://dx.doi.org/10.1016/j.fuel.2016.07.076
0016-2361/

Nomenclature

CSC	critical salinity concentration
CEC	cation exchange capacity
C_{eff}	concentration of effluent
DLVO	Derjaguin and Landau, Verwey and Overbeek theory
EDL	electrical double layer
FTIR	fourier transform infrared Spectroscopy
LSW	low salinity water
LSWF	low salinity water flooding
OOIP	original oil in place
ORF	oil recovery factor
PPM	part per million
PV	pore volume
TDS	total dissolved solids
XRD	X-ray diffraction

more acceptable among the aforementioned mechanisms. Hence, LSWF is considered as an enhanced oil recovery technique due to its effect on wettability alteration [2,3].

According to reviews by Austad et al. (2010) and Sheng (2014), the presence of clays, connate water, and polar crude oil is necessary for a successful LSWF operation in sandstone formations [2,3]. Emadi and Sohrabi (2013) observed the formation of water micro-dispersions via micromodel during LSWF. They proposed the swelling of connate water droplets and wettability alteration as mechanisms, but their synthetic porous media (a glass micromodel) lacked clay minerals [4]. Jadhunandan and Morrow (1995) proposed that the wettability depends on the initial water saturation. With rising initial water saturation, the wettability will be more water-wet, which was supported by Zhang and Morrow (2006), who pointed out that to achieve a positive effect of LSW, the presence of connate water is required [5,6].

Pore spaces of most sandstone reservoirs contain different clay minerals created by the sand grains. Kaolinite, illite/mica, chlorite, and smaller contents of montmorillonite are common clays present in the sandstone reservoirs. Formations with high clay content are often sensitive to water and when exposed to fresh water tend to undergo hydration and dispersion. Studies have shown that a decrease in the salinity of brines below the critical salt concentration (CSC) causes expansion or mobilization of clays [7]. In recent decades, various studies have been carried out on the role of clay minerals in LSWF.

An experimental study performed by Martin (1959) indicated that swelling of clay and emulsification are major reasons for enhanced heavy oil recovery during LSWF [8]. Bernard (1967) reported that improvement of oil recovery in cores containing clays is associated with a reduction of permeability and an increment of pressure drop across the cores [9]. Sharma and Yortsos (1987) and Vaidya and Fogler (1990) observed that the mobilization and relocation of fines particles in the reservoirs are more affected by the alteration of brine composition [10,11]. The presence of clays or potentially mobile fines as one of the necessary conditions for LSW effects was proposed for the first time by Tang and Morrow (1999). This mechanism is based on the adsorption of heavy or polar components on the surface of the pore walls that are coated by clays and release of fine particles with clinging oil droplets due to the electrical double layer force between clays during LSWF [12]. A direct relationship between oil recovery enhancement by LSWF and the presence of kaolinite in porous media was observed by Jerauld (2006) and Seccombe (2008) [13,14]. In addition, the relocation of clay particles in the porous medium by LSWF can seal off some of the pore-throats, deflect the flow into unswept pore-throats, and finally promote microscopic sweep efficiency [15]. Unexpectedly, Austad (2010) posed that kaolinite, due to its low cation exchange capacity (CEC), would be the least desirable clay for low-salinity flooding [16]. Also, several researchers have reported positive effects of LSWF in low clay content or clay-free sandstone samples without production of fines in the effluent [16–18].

Table 1
Characterization of sodium bentonite.

Specification	Value
Montmorillonite (mass %)	62.3
Feldspar (mass %)	13.9
Cristobalite (mass %)	9.6
Quartz (mass %)	9.7
Anorthite (mass %)	2
Gypsum (mass %)	1.1
Muscovite (mass %)	0.9
Calcite (mass %)	0.5
CEC (meq/100 g)	64.7
Average particle size (μm)	3

Setting aside the aforementioned observations, two different roles have been mentioned for the fines migration phenomenon in oil reservoirs: (1) a positive role in terms of oil recovery enhancement, [12,15], and (2) a negative role in terms of productivity reduction [19,20].

Assuming that the fine–pore surface is a sphere–plate system, the major forces responsible for releasing fines are colloidal and hydrodynamic forces. The total energy of interplays has five parts, and if the total sum of these forces becomes repulsive, release of the fine particles may begin. These forces are as follows [20]:

(1) EDL (repulsion).
(2) London–Van der Waals (attraction).
(3) Born (repulsion).
(4) Acid–base interaction (attraction or repulsion).
(5) Hydrodynamic (repulsion).

When the interaction distance between fines and the surface of pore walls is greater than 1 nm, the Born repulsion force is too small and can be ignored. Besides, acid–base interaction is about one to two orders of magnitude less than the double layer repulsion and London–Van der Waals attraction; therefore, it can also be ignored. Hence, the three major forces are DLVO[1] (EDL and London–Van der Waals) and hydrodynamic [21,22]. If the salinity of flowing fluid is reduced below the CSC, the double layer repulsion force increases dramatically and the total interaction becomes repulsive. Also, with an increase in the pH of the flowing fluid due to the variation in Zeta potential, the total interaction towards repulsive [23]. Cerda (1987, 1988) also pointed out that the hydrodynamic force is only considerable for large fines particles at high flow velocity [24,25]. The conventional velocity of field flooding is 1 ft/day, while velocities of 10 and 16 ft/day are rarely seen [26]. Therefore, most of the flow through porous media is laminar and hydrodynamic force can be disregarded.

According to previous discussions, there are challenges regarding the effect of clay minerals and fines mobilization during LSWF. In this work, we presented a novel method for depositing a particular clay in the micromodel and ultimately fabricated a clayey

[1] DLVO theory named after Derjaguin, Landau, Verwey and Overbeek.