THE EFFECT OF KAOLINITE ON OIL RECOVERY BY LOW SALINITY WATERFLOODING IN SANDSTONE RESERVOIRS

DANIAL AZIM CHE AZIZ¹, ERFAN MOHAMMADIAN^{2*}, NOR ROSLINA ROSLI¹, NAZRUL HIZAM
YUSOFF³ & NORAISHAH OTHMAN³

¹Faculty of Chemical Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia

²Cyprus International University, Department of Petroleum and Natural Gas Engineering, Nicosia, TRNC, via Mersin 10, Turkey.

³Nuclear Malaysia, Kajang, Selangor, Malaysia

ABSTRACT

Low salinity waterflooding (LSW) is a new method by which the recovery from oil reservoirs can be enhanced. This work focuses on the impact of kaolinite concentration on the oil recovery by LSW. The LSW experiments were conducted using sandpacks with varying concentrations of kaolin clay (5wt%, 10wt% and 15wt%). Kerosene was used as the model oil phase in this work. Test results showed an increase of recovery with increasing kaolinite concentration. Highest oil recovery was obtained at 74% of Original Oil in Place (OOIP) at 5 wt% kaolinite concentration while the lowest was observed at 55% of OOIP at 15 wt% kaolinite concentration. During experimentation, low initial oil saturation was achieved with the kerosene. Water breakthrough occurred much faster in higher concentration kaolinite sandpack. The increase in pH and multi-component ionic exchange (MIE) mechanisms were evaluated based on the pH values and final Mg^{2+} and Ca^{2+} concentration of the produced water. Concentrations of the Mg^{2+} and Ca^{2+} showed a decrease as compared to the initial formation water and low salinity brine in all experiments.

KEYWORDS: Low salinity waterflood, Kaolinite, multi-component ion exchange, Enhanced Oil Recovery, RTD

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1.INTRODUCTION

Oil is primarily recovered by the reservoir natural drive mechanism which are; solution gas, water influx, gas cap drives and/or gravity drainage. However, to further improve production, secondary or tertiary recovery mechanisms tend to be applied. One of the most common method for oil recovery in the world is waterflooding. The attractiveness of waterflood stems from the general availability of water, relative simplicity of the injection, good spreading in the oil reservoir and its high displacement efficiency (Sheng, 2013).

LSW is a relatively new method in which low salinity brine is injected to the reservoir to enhance the oil recovery. Low-salinity (LS) water is economically an interesting option due to availability of water and its relative cheap price as compared to other enhanced oil recovery (EOR) methods. From technical point of view also, variety of lab tests, and a few field studies has proven the efficiency of LSW over conventional waterflooding in majority of (not all) of the cases (AlQuraishi et al., 2015; Gomari et al., 2006; Jackson et al., 2016). Variety of factors affect the success of LSW, such as connate water saturation, timing of injection, injection fluid composition and rock and fluid properties (Tang & Morrow, 1999; Yildiz & Morrow, 1996). Oil recovery generally increased during the LSW when applied as secondary recovery method. The effects of wettability on recovery of LSW in a field trial reported

increased in oil production as a result of LSW (Alotaibi et al., 2010). Generally, majority of previous researchers reported that LSW has a positive effect on enhancing the oil production when the salinity of injection water is lower than that of connate water. Although some of the mechanisms by which LSW increased the recovery is known, more research is still required to further enhance the understanding regarding the application of LSW prior to large scale industrial implementation of LSW for EOR purposes.

The process of LSW has been widely studied well-established. However, most of previous studies were conducted in carbonate cores and limited study in sandstone cores (Azreen Jilani et al., 2015; Honarvar et al., 2017). In more realistic conditions, reservoirs contain various types and concentrations of shales as well. This experimental work attempts to assess the effect of the presence and concentration of clay in sandpack on the improved oil recovery by LSW. The clay particles on sand provide the negatively charged surface for the adsorption of the polar components of crude oil which would alter the rock surface to an oil-wet state. Furthermore, the clay minerals would also act as an ion exchanger when it comes into contact with the oil, thereby, resulting in a decrease in cation concentration in the produced water or pH increase (Tang & Morrow, 1999).

2. METHODOLOGY

2.1 Materials

The sand that was used for the experiment was collected from Bagan Lalang Beach (2.6039° N, 101.6881° E), Selangor, Malaysia. The collected sand was oven dried for 2 to 3 hours at 80°C and sieved up to 150µm using a digital sieve shaker (Endecotts Octagon 2000). Kaolin clay powder (R&M Chemicals) was utilized in this work. Kaolinite is 1:1 type clay and contains a tetrahedral sheet of silicon (SiO₄) and an octahedral sheet of aluminum in one layer and the layers are placed sequentially one above the other. Kaolinite is not chemically inert and does possess a small net negative charge due to broken bonds at the edges of the kaolinite particles. These small negative charges are stabilized by minor cationic substitutions. The least reactive clay particle in sandstone reservoirs is kaolinite, and it is also classified as a non-swelling type of clay particle (Mohd & Jaafar, 2019). Due to lower surface area and less substitutions occurring, they have low cation exchange capacity (CEC) and hence low reactivity (Yildiz & Morrow, 1996).

Three samples of brines (formation water, synthetic seawater, and 10x diluted seawater) were prepared for the experiment based on modifications of a previous study (Alotaibi et al., 2010). The effects of LSW is only observable at salinity lower than 5000 ppm (Nasralla et al., 2016). Therefore, the synthetic seawater was diluted ten times. Properties of the studies brines are presented in Table 1.

Table 1: Injected brine composition

	Formation water	Synthetic Seawater	10x diluted seawater (LSW)
NaCl (g/L)	28.29	11.35	1.13
CaCl (g/L)	0.88	0.47	0.04
MgSO ₄ (g/L)	0.07	1.440	0.14
TDS (ppm)	29260	13265	1326.50
pH	7.16	7.21	7.89

Kerosene was used as the oil for this experiment. Density of kerosene is 0.8 g/cm³ and its viscosity is 1.64 cp. Hence, based on its physical characteristics, kerosene resembles a low-viscosity light oil. The schematics of the system that

was used in the experiments is shown in Figure 1. This schematic shows the layout for the sandpack waterflooding system, which is divided into three sections: the upstream, the sandpack column and the downstream.

Figure 1: Core Holder 1 flooding set up

The upstream side of the system provides the intermittent injection of brines (formation water, seawater, LSW) and kerosene. It consists of a syringe (60 ml and 150 ml) and a syringe pump (NE-1000, New Era Pump System Inc). The syringe was connected to the pipe fittings of the column through a 7 mm ID clear tubes. The downstream section consists of a 25 ml measuring cylinder for collection of effluents. The use of a small measuring cylinder was for easier reading of liquid value at each interval of injection as it had to be taken manually. The stainless steel sand pack column dimensions are 35 cm length, 5.5 cm diameter, and thickness of 0.2 cm.

2.2 Sandpack Preparation

The sand pack preparation method involved dry mixing of kaolin and sand, which were then wetted with 200 ml of ultrapure water and then placed in an oven for 2 to 3 hours at 90°C to dry completely. The dried kaolinite and sand mixture were then sieved up to 300 μm to 150 μm for 15 minutes on a digital sieve shaker at 8 amplitudes. Pure sand sample, pure kaolinite and mixed sand and kaolinite samples were analyzed using Scanning Electron Microscopy (Model GeminiSEM 500) to determine the difference. The mixture was then placed in the horizontal sandpack column.

Sand pack was prepared by packing the sand sample inside a horizontal sand pack of known volume and saturated with formation water. The volumes were measured, and kerosene was then injected to establish initial saturation. Once the initial oil saturation (S_{oi}) and initial water saturation (S_{wi}) have been established through displacement with kerosene, all tubing and fittings were drained, and the column was let to set for aging process. The aging process were done overnight at room temperature. The characterization of each sandpack is summarized in Table 2. The presented measurements are average of 3 times run for each data series (kaolinite concentration). Waterflooding tests were conducted once the sandpack has been aged. LSW brine was injected intermittently using a syringe pump at a rate of 1 mL/min. The injection of brine displaced the oil originally in place in the core holder. The amount of oil produced at effluent was collected and the values were recorded at every interval of 5 ml. The produced fluid was then analyzed using a pH meter and an Atomic Absorption Spectroscopy (AAS) to measure the changes in the Mg^{2+} and Ca^{2+} ions concentrations.

Table 2: Sandpack conditions

Kaolin concentration, wt%	Average Porosity, %	Average S_{oi}	Average S_{wi}
5	0.39	0.49	0.51
10	0.38	0.28	0.72
15	0.35	0.22	0.78

3. RESULTS AND DISCUSSIONS

3.1 FESEM Analysis

Figure 2 shows the microscopic image of the sand samples. The average particle size for pure sand as shown in Fig. 2a was found to be in the range of 150 to 300 μ m. The sample from pure sand was homogenous. The unsieved sample of kaolinite sand (Figure 2 c and b, respectively) showed a more variation in its grain size. The coating of the sample that was prepared through dry mixing was superficial as the kaolin particle can be seen to simply sit atop the sand particle, which can be observed in Figure 2c. The coating in Figure 3d sample (wetted and dried mix) seems to be more subtle and its surface seems to be more even.

Figure 2: Microscopic image of (A) pure sieved sand (B) pure kaolin powder, (C) kaolinite sand

3.2 Oil Recovery

Normal waterflooding was conducted on the sandpack (containing same amount of clay as LSW experiments) to provide a benchmark to compare the LSW results to. The experiments were repeated 3 times and the average recovery of normal waterflooding in the experiments was 35.5%. The high recovery factor of normal waterflooding was due to low viscosity of kerosene and high permeability porous media (as a result of using loose sand). It can be observed in Figure 3 that a higher kaolin content resulted in a higher overall recovery for all concentrations. The results are in line with authors previous work using clean sandpacks of various configurations (Mohammadian et al., 2013, 2011).

Oil recovery factor increased from 0.10 to 0.36 which resulted in total recovery factor of 0.46 to 0.71 as a result of LSW of sandpacks with kaolinite content from 5 to 15 %. These results coincided with previous studies whereby their studies also showed an increasing recovery trend with an increase of the kaolinite concentration in the core during LSW (Jerauld et al., 2008; Seccombe et al., 2008; Zhang et al., 2007).

Figure 3: Percentage of OOIP Recovered by Conventional LSW Experiments

This is aligned with results from several previous studies which concluded that clay concentration does not act as the primary mechanism for the increase in oil recovery by LSW but instead, improvement of oil recovery was believed to be more influenced by the distribution of clay (Jerauld et al., 2008; Lager et al., 2008; Seccombe et al., 2008). Oil recovered at each interval of 5 ml was recorded for all experiment. Figure 4 compiles all the data obtained to allow better visualization. It can be concluded that water breakthrough generally occurs faster in sandpacks with higher kaolinite concentration. This again, may be attributed to its higher tendency of fracturing as kaolinite may have blocked open pores thus continuous injection into the sandpack would cause pressure to increase to a point greater than fracture pressure of the sandpack. The increasing pressure would then induce fractures in the sandpack causing channeling of the injected water.

Figure 4: Oil Recovery vs PV Injected

3.3 Analysis of pH increase mechanism

Analysis of the pH of produced water was done to compare the possible activity of pH increase mechanisms for improved oil recovery by LSW. The initial pH for the formation water and low salinity water was recorded at 7.16 and 7.85 respectively. As can be seen in Table 3, the produced water from the set A and set B experiments showed slight increase in produced water from the initial pH of the formation brine and low salinity brine. The increase in pH is more pronounced at 15% kaolin concentration. Hence, it can be concluded that the pH of effluent brine is directly affected by the concentration of kaolin.

The visual analysis of sandpack has not shown any channels (fractures) for the 15% kaolin concentration experiment. Thus, it is assumed that the low salinity brine was well dispersed within the sandpack during injection as compared to set 5 and 10% kaolin content which exhibits some channeling. The presence of fractures or channels is due to use of loose sand to create the sand pack.

Table 3: Results of the LSW

Kaolin concentration, wt%	Average Porosity	Average pH of produced water	Average OOIP recovered
5	0.39	7.87	0.55
10	0.38	7.89	0.61
15	0.35	7.95	0.74

3.4 Analysis of MIE Mechanism

The analysis of produced water showed an increase in presence of Mg^{2+} and Ca^{2+} as compared to the initial concentration present in formation water. This suggested that the previously cited MIE mechanisms for the increase in oil recovery by LSW was not active (Lager et al., 2008). It should be noted that this result may have been caused by the lower initial Mg^{2+} ions in the abridged formulation of formation water which was used than in the low salinity brine (Zhang et al., 2007). Lager et al., (2008) explained MIE as the cation exchange of the mineral surfaces and the injected brine. It was suggested that this cation exchange would occur by a strong presence of Mg^{2+} and Ca^{2+} gradient between the initial formation water and the injected brine. This, however, was not the case for the formulated low salinity brine (LSB) composition used in this study.

Figure 5(a): Concentration of Ca^{2+} in the produced water, (b): Concentration of Mg^{2+} in the produced water

Thus, as can be seen in Figure 5a and Figure 5b all produced water experienced an increase in salinity from the initial 19.87 ppm of Mg^{2+} and 674.4 ppm Ca^{2+} of formation water to 34.14 ppm of Mg^{2+} and 51.69 ppm Ca^{2+} of LSB. This suggested that cation exchange may have occurred in the reversed direction, whereby the initially absorbed cations were desorbed off the clay sands during flooding with LSB. Thus, it was believed that the modified brine composition from Zhang et al., (2007) was not suited for the activation MIE mechanism in LSW. This was because of the lower Mg^{2+} concentration in formation water than in LSB. In comparison, other studies were shown to utilize a formation brine of a much higher Mg^{2+} and Ca^{2+} concentration as compared to the LSB the same results were reported in some of previous studies (Law et al., 2015; Nasralla & Nasr-El-Din, 2012; Shaker Shiran & Skauge, 2013).

4. CONCLUSIONS AND RECOMMENDATIONS

In this work, low salinity waterflooding was conducted on a sand column with various concentrations of kaolinite clay. The recovery factor of LSW increased in all the experiments regardless of the clay concentration. The analysis of effluents revealed that, the pH of all effluents increased which indicated pH mechanism is effective on the recovery of LSW. Moreover, the analysis of effluent brine showed a decrease in Mg^{2+} and Ca^{2+} concentrations. From point of view of recovery factor, LSW was proven to be effective as it increased the oil recovery from 10 to 36% from the benchmark, being normal waterflooding injection using formation brine (~29,000 ppm brine). It therefore can be concluded that LSW can be an effective method in presence of kaolin clay. The effect of other types of clay can be investigated to improve the understanding of the effects of type and concentration of clay on efficiency of waterflooding.

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