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Studying low-salinity waterflooding recovery effects in sandstone reservoirs

Ahmad Aladasani [a], Baojun Bai [b], Yu-Shu Wu [c], Saeed Salehi [d]

[a] Planning and Support (Heavy Oil), Kuwait Oil Company, Ahmadi, Kuwait
[b] Petroleum Engineering Department, Missouri University of Science and Technology, Rolla, MO., USA
[c] Petroleum Engineering Department, Colorado School of Mines, Golden, CO., USA
[d] Petroleum Engineering Department, University of Louisiana, Lafayette, LA., USA

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ABSTRACT

Numerous core-flooding experiments have shown that low-salinity water flooding (LSWF) could improve oil recovery in sandstone reservoirs. However, LSWF recovery effects remain highly contentious primarily because of the absence of crucial boundary conditions (boundary conditions are defined throughout the paper as the initial and final, contact angle and interfacial tension values). The objective of this paper is to conduct a parametric study using statistical analysis and simulation to measure the sensitivities of LSWF recovery effects in sandstone reservoirs. The summary of 411 core-flooding experiments discussed in this paper highlights the extent and consistency in reporting boundary conditions, which has two implications for statistical analysis: (1) the statistical correlations of the residual oil saturation to chlorite (0.7891) are strong, whereas the statistical correlations of the residual oil saturation to kaolinite (0.4399) contents, as well as to the wettability index (0.3890), are comparably lower, the majority of dataset entries are missing, and no prediction model can be generated; (2) if a prediction model is generated without clay content values and a wettability index, even though LSWF effects emphasizes wettability modification by virtue of oil aging time and the strong influence of brine cation and divalent ion concentrations on S_{or}, the prediction model's regression curve and confidence level are poor. Reservoir simulations conducted to examine LSWF recovery sensitivities conclude that LSWF recovery effects are governed based on the initial and final wetting states. In all wetting states except for weak water-wet conditions, the increase in oil relative permeability is the underlining recovery effect. In weak water-wet conditions, LSWF incremental recovery is driven by low capillary pressures. In weak oil-wet conditions, the secondary LSWF recovery effect is the change of the non-wetting phase to oil. In all wetting states, an appreciable decrease in interfacial tension (IFT) is realized at the breakthrough recovery. The decrease in IFT is the primary recovery effect in strong water-wet conditions.

1. Introduction

Numerous core-flooding experiments have shown that low-salinity water flooding (LSWF) could improve oil recovery in sandstone reservoirs. Bernard's work in 1967 served as the impetus behind LSWF core-flooding experiments and perhaps low saline solution flooding in other water-based enhanced oil recovery (EOR) methods for the following reasons: (1) core-flooding experiments were conducted on outcrop Berea and Wyoming cores; (2) the results indicated that LSWF improves oil recovery at both the secondary and tertiary stages; (3) residual oil saturation decreased notably when the NaCl weight percentage was reduced from 1% to 0.1%; (4) salinity was advocated as a variable that impacts the efficiency of waterfloods; (5) although the study falls short in detailing oil desorption from the reservoir rock and favorable wettability modifications, the study does attribute incremental recovery from LSWF to fine particle dispersion. Research involving other water-based EOR methods, such as polymer flooding (Paul and Froning, 1973), showed that low-salinity solutions improved the efficiency of polymer drive oil displacement. In addition, several miceller and surfactant flooding field trials have concluded that low-salinity flooding solutions and low divalent ion concentrations can augment oil production (BP, 1979).

The second milestone in the development of LSWF came 30 yrs later when Tang and Morrow (1997) associated LSWF incremental recovery with favorable wettability modification and, 2 yrs later, presented the first LSWF recovery mechanism (Tang and Morrow, 1999a, 1999b). Despite the significance of their contribution,

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Nomenclature

IFT	interfacial tension
B_w	water formation factor
σ	interfacial tension
B_β	phase β formation factor
S_g	gas saturation
B_w^o	water formation factor at P_b^o
S_o	oil saturation
C_w	water phase compressibility
S_w	water saturation
μ	viscosity
S_{gr}	residual gas saturation
μ_β	phase B viscosity
S_{or}	residual oil saturation
μ_o	oil viscosity
S_{wc}	critical water saturation
μ_w	water viscosity
S_{org}	residual gas oil saturation
M	mobility ratio
S_{gc}	critical gas saturation
λ	mobility ratio
S_{oi}	initial oil saturation
γ	transmissivity
k	permeability
ψ	potential
$k_{r\beta}$	phase β relative permeability
ppm	parts per million
k_{rg}	gas relative permeability
PV	pore volume
k_{ro}	oil relative permeability
g	gas
k_{rw}	water relative permeability
w	water
k_{ro}^{*wo}	oil relative permeability at critical water saturation
o	oil
k_{ro}^{wo}	oil relative permeability in 2-phase oil–water system
ϕ	porosity
k_{ro}^{og}	oil relative permeability in 2-phase oil–gas system
X_c	mass fraction of salt component in the water phase
P_g	gas capillary pressure
X_w	mass fraction of water component in the water phase
P_o	oil capillary pressure
ρ	density
P_w	water capillary pressure
ρ_R	rock grain density
P_β	phase capillary pressure
∇	flux
P_{cgo}	oil gas capillary pressure
ν	Darcy velocity
P_{cow}	water oil capillary pressure
q	flowrate
P_g	bubble point pressure
K_d	salt distribution coefficient between water phase and reservoir rock
P_b^o	initial bubble point pressure
D_m	molecular diffusion coefficient
θ	theta (contact angle)
τ	formation tortuosity
B_g	gas formation factor
P	pressure
B_o	oil formation factor
g	gravity constant
B_w	water formation factor
d	surface depth
B_β	phase β formation factor
B_w^o	water formation factor at P_b^o
Φ	potential
C_w	water phase compressibility
STC	standard tank condition
B_w	water formation factor
R_s	solution gas–oil ratio
B_β	phase β formation factor

rather than attention being drawn to the importance of identifying all boundary conditions in core-flooding experiments, the scientific community turned its focus on identifying LSWF recovery mechanisms and effects. Without knowing critical boundary conditions, several theories were presented, all of which, as expected, were difficult to prove.

The first recovery mechanism suggested for LSWF was the partial stripping of mix-water fines, illustrated in Fig. 1 (Tang and Morrow, 1999a, 1999b), which was questioned in experiments conducted by Zhang et al. (2007) that showed no evidence of clay content in the production stream or the oil/brine interface. The sandstone reservoir is assumed to have a negative charge. The fines comprise of species with dual polarities. During high salinity waterflooding the ionic environment is charged and the fines are adsorbed onto the matrix (the attractive force dominants) thus fines remain adsorbed and do not migrate. By contrast in case the formation water ionic environment is weakened (low-salinity waterflooding) the fines are desorbed from the matrix (repulsive forces dominant).

The second recovery effect suggested for LSWF was the reduction in interfacial tension (IFT) due to an increase in pH values (McGuire et al., 2005), which similarly was questioned in experiments conducted by Lager et al. (2006) showing that LSWF incremental recovery in brine had a pH of less than 7.

The second recovery mechanism suggested for LSWF was based on the concept that multivalent cations bridge the negatively charged oil to the clay minerals (Anderson, 1987; Fairchild et al., 1988; Israelachvili, 1991; Buckley et al., 1989; Liu et al., 2005). In the context of LSWF, Lager et al. (2007) suggested multi-component ionic exchange (MIE), illustrated in Fig. 2. Similar to the partial stripping of mix-water fines the sandstone reservoir is assumed to have a negative charge. As the formation of water is de-ionized (LSWF) the double layer expands due to the weakening attractive force (reduction in cation concentrations). Oil gradually desorbs from the matrix as the repulsive forces become more dominant. MIE resulted in oil desorption when low electrolyte water was used for water flooding, especially Mg^{2+} exchange, which was confirmed by measuring the magnesium content in the produced water (Lager et al., 2007; Alotaibi et al., 2010). This result also was supported by Lee et al. (2010). However, Austad et al. (2010) suggested that polar oil components also can adsorb onto clay minerals without bridging divalent cations, and a reduction in magnesium content can be caused by precipitation, such as $Mg(OH)_2$, especially at increased pH levels during LSWF.

Furthermore, Ligthelm et al. (2009) also suggested that cation striping is not an essential factor in wettability modification. The third LSWF recovery mechanism suggested a relationship between the mineral content kaolinite in clays and the LSWF incremental recovery (Seccombe et al., 2008). However, Cissokho's et al. (2009) experimental findings concluded substantial LSWF incremental recovery in kaolinite-free cores. More than likely, LSWF can create multiple favorable recovery conditions (Austad et al., 2010;