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# Studying low-salinity waterflooding recovery effects in sandstone reservoirs



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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<sub>or</sub>, 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 nonwetting 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.

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### 1. Introduction

Numerous core-flooding experiments have shown that lowsalinity 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,

$ \begin{array}{ll} FT & \operatorname{interfacial tension} & X_c & \operatorname{mass fraction of salt component in the water phase \\ B_w & water formation factor & P_g & gas capillary pressure \\ \hline \sigma & \operatorname{interfacial tension} & X_w & \operatorname{mass fraction of salt component in the water phase \\ \hline g & phase \beta formation factor & P_o & di capillary pressure \\ \hline S_e & gas saturation & \rho & density \\ B_w^w & water formation factor at P_p^0 & P_w & water capillary pressure \\ \hline S_o & di saturation & \rho & density \\ \hline S_w & water saturation & \nabla & flux \\ \hline V & water saturation & \nabla & flux \\ \mu & viscosity & P_{cg0} & oil gas capillary pressure \\ \hline S_{gr} & residual gas saturation & \varphi & flux \\ \mu & viscosity & P_{cg0} & oil gas capillary pressure \\ \hline S_{gr} & residual gas saturation & q & flowrate \\ \mu_0 & di Viscosity & P_{cg0} & oil gas capillary pressure \\ \hline S_{gr} & residual di saturation & q & flowrate \\ \mu_{do} & oil viscosity & P_{gs} & bubble point pressure \\ \hline S_{gr} & residual gas di saturation & R_d & salt distribution coefficient between water phase and reservoir rock \\ \hline S_{org} & residual gas di saturation & P_b^{h} & initial bubble point pressure \\ \hline M_{m} & water viscosity & P_{gs} & bubble point pressure \\ \hline M_{gr} & phase surve (contact angle) \\ \hline \lambda & mobility ratio & D_m & molecular diffusion coefficient \\ \hline S_{gr} & ritical water saturation & B_g & gas formation factor \\ \hline \gamma & transmissivity & P & pressure \\ \hline \lambda_{erg} & patse p relative permeability & B_{er} & water formation factor \\ \hline \gamma & transmissivity & P & pressure \\ \hline \lambda_{erg} & gas relative permeability & B_{gr} & phase f formation factor \\ \hline P & portential \\ \hline \lambda_{erg} & gas formation factor & P_b^{h} & pressure \\ \hline \lambda_{erg} & gas relative permeability & Trice and the condition \\ \hline \lambda_{erg} & gas relative permeability & STC & standard tank condition \\ \hline \lambda_{erg} & gas \\ \hline 0 & oil relative permeability at critical water saturation \\ \hline \lambda_{erg} & oil relative permeability a critical water saturation \\ \hline \lambda_{erg} & oil relative permeability a critical water saturation \\ \hline \lambda_{erg} & oil relative permea$	Nomenclature		$\phi_{1,0g}$	porosity
$ \begin{array}{ll} IF & \mass fraction of salt component in the water phase \\ B_w & water formation factor & P_e & gas capillary pressure \\ \sigma & \mass fraction of water component in the water phase \\ B_{\beta} & \mbox{phase } \beta formation factor & P_o & \mbox{oil capillary pressure} \\ \beta_w & \mbox{water formation factor at $P_o^{\mbox{phase } P_v & \mbox{water formation factor $P_o^{\mbox{phase } P_v & \mbox{water phase } \mbox{mox mase } \mbox{phase } p$			$K_{ro}^{-3}$	oil relative permeability in 2-phase oil-gas system
$ \begin{array}{lll} \begin{array}{llllllllllllllllllllllllllllll$	IFT	interfacial tension	X <sub>c</sub>	mass fraction of salt component in the water phase
σinterfacial tensionXwmass fraction of water component in the water phase $B_{\beta}$ phase β formation factorPooil capillary pressure $B_{w}$ water formation factor at $P_{b}^{o}$ Pwwater capillary pressure $S_{o}$ oil saturationProck grain density $C_{w}$ water phase compressibilityPfphase capillary pressure $S_{w}$ water saturationVflux $\mu$ viscosityPcoil gas capillary pressure $S_{w}$ water saturationVDarcy velocity $\mu_{\mu}$ viscosityPcowwater oil capillary pressure $S_{gr}$ residual gas saturation $\mu$ Darcy velocity $A_{\mu}$ viscosityPcowwater oil capillary pressure $S_{or}$ residual oil saturation $q$ flownate $M_{o}$ oil viscosity $P_{g}$ bubble point pressure $S_{org}$ critical gas oil saturation $P_{b}^{h}$ initial bubble point pressure $M_{w}$ water viscosity $T$ formation factor $S_{gg}$ critical gas saturation $P_{b}^{h}$ initial bubble point pressure $M_{w}$ mobility ratio $T$ formation factor $S_{gg}$ critical gas saturation $P_{b}^{g}$ initial bubble point pressure $S_{gg}$ critical gas saturation $P_{b}^{g}$ initial bubble point pressure $M_{w}$ mobility ratio $T$ formation factor $S_{gg}$ critical gas saturation $P_{g}^{g}$ gas formati	$B_w$	water formation factor	$P_g$	gas capillary pressure
$\begin{array}{llllllllllllllllllllllllllllllllllll$	$\sigma$	interfacial tension	$X_w$	mass fraction of water component in the water phase
$\begin{array}{cccc} & gas saturation & \rho & density \\ B^{G}_w & water formation factor at P^{G}_b & P_w & water capillary pressure \\ S_0 & \text{oil saturation} & \rho_R & \text{rock grain density} \\ C_w & water phase compressibility & P_{g} & phase capillary pressure \\ S_w & water saturation & P_R & \text{oil gas capillary pressure} \\ & viscosity & P_{ggo} & \text{oil gas capillary pressure} \\ S_{gr} & \text{residual gas saturation} & \nu & \text{Darcy velocity} \\ \mu_{f} & \text{phase B viscosity} & P_{ggo} & \text{oil gas capillary pressure} \\ S_{gr} & \text{residual oil saturation} & q & \text{flowrate} \\ \mu_a & \text{oil viscosity} & P_g & \text{bubble point pressure} \\ S_{gr} & \text{critical water saturation} & q & \text{flowrate} \\ \mu_a & \text{oil viscosity} & P_g & \text{bubble point pressure} \\ S_{wc} & \text{critical water saturation} & R_g & \text{bubble point pressure} \\ S_{wc} & \text{critical gas oil saturation} & P_g^{B} & \text{initial bubble point pressure} \\ M_w & water viscosity & molecular diffusion coefficient between water phase and reservoir rock \\ S_{org} & \text{residual gas oil saturation} & \beta_{\mathfrak{B}} & \text{moleily ratio} & \text{contation factor} \\ S_{ge} & \text{critical gas saturation} & \theta & \text{theta} (\text{contact angle}) \\ \lambda & \text{mobility ratio} & T & \text{formation factor} \\ S_{ge} & \text{premability} & P & \text{pressure} \\ k & \text{permeability} & B_{g} & \text{gaf ormation factor} \\ \psi & \text{potential} & g & \text{gravity constant} \\ K_{gg} & \text{gas relative permeability} & B_{g} & \text{phase } \beta \text{ formation factor} \\ P_{go} & \text{potential} \\ K_{gg} & \text{gas lative permeability} & \mathcal{P} & \text{potential} \\ K_{go} & \text{oil relative permeability} & \mathcal{P} & \text{potential} \\ K_{gg} & \text{gas lative permeability} & \mathcal{P} & \text{potential} \\ K_{gg} & \text{gas lative permeability} & \mathcal{P} & \text{potential} \\ K_{gg} & \text{gas} \\ R_{go} & \text{oil relative permeability} & \mathcal{P} & \text{potential} \\ g & \text{gas} \\ K_{go} & \text{oil relative permeability} & \mathcal{P} & \text{potential} \\ g & \text{gas} \\ R_{go} & \text{oil relative permeability} & \text{critical water saturation} \\ R_{g} & \text{gas contant} \\ R_{go} & \text{oil relative permeability} & critical water saturatio$	$B_{\beta}$	phase $\beta$ formation factor	$P_o$	oil capillary pressure
$B_w^0$ water formation factor at $P_b^0$ $P_w$ water capillary pressure $S_o$ oil saturation $\rho_R$ rock grain density $C_w$ water phase compressibility $P_g$ phase capillary pressure $S_w$ water saturation $V$ flux $\mu$ viscosity $P_{cgo}$ oil gas capillary pressure $S_{gr}$ residual gas saturation $\nu$ Darcy velocity $\mu_{\beta}$ phase b viscosity $P_{cow}$ water oil capillary pressure $S_{or}$ residual oil saturation $q$ flowrate $\mu_o$ oil viscosity $P_g$ bubble point pressure $S_{orc}$ critical water saturation $K_d$ salt distribution coefficient between water phase and reservoir rock $S_{org}$ residual gas oil saturation $P_b^0$ molecular diffusion coefficient $M_w$ water viscosity $T$ formation factor $S_{gc}$ critical water saturation $B_g$ gas formation factor $M_w$ mobility ratio $T$ formation factor $S_{gc}$ critical saturation $B_g$ gas formation factor $\gamma$ transmissivity $P$ pressure $k_{fg}$ phase $\beta$ relative permeability $B_w$ $water formation factorP_b^0sutace depthk_{rg}gas relative permeabilityB_g\phioptentialK_{corr}K_{rg}gas relative permeability\Phi\phioptentialK_{rg}K_{rg}gas relative permeability<$	Sg	gas saturation	$\rho$	density
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$ \begin{array}{llllllllllllllllllllllllllllllllllll$	$C_w$	water phase compressibility	$P_{\beta}$	phase capillary pressure
$ \begin{array}{cccc} \mu & \mbox{viscosity} & P_{cgo} & \mbox{oil gas capillary pressure} \\ S_{gr} & \mbox{residual gas saturation} & \nu & \mbox{Darcy velocity} \\ \mu_{\beta} & \mbox{phase B viscosity} & P_{cow} & \mbox{water oil capillary pressure} \\ S_{or} & \mbox{residual oil saturation} & q & \mbox{flowrate} \\ mo & \mbox{oil viscosity} & P_g & \mbox{bubble point pressure} \\ S_{wc} & \mbox{critical water saturation} & K_d & \mbox{salt distribution coefficient between water phase and mobility ratio} & \mbox{momodul reservoir rock} \\ S_{org} & \mbox{residual gas oil saturation} & P_b^o & \mbox{initial bubble point pressure} \\ M & \mbox{mobility ratio} & \mbox{momodul ration} & \mbox{momodul reservoir rock} \\ S_{gc} & \mbox{critical gas saturation} & \mbox{momodul ration} & \mbox{momodul ratio} & \mbox{momodu ratio} & \mbox{momodul ratio} & \mbox{momodul ratio} & \mbox{momodu ratio} & \mbomodu ratio & momodu r$	$S_w$	water saturation	$\nabla$	flux
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$ \begin{array}{cccc} \mu_{\beta} & \mbox{phase B viscosity} & P_{cow} & \mbox{water oil capillary pressure} \\ S_{or} & \mbox{residual oil saturation} & q & \mbox{flowrate} \\ \mu_{o} & \mbox{oil viscosity} & P_{g} & \mbox{bubble point pressure} \\ S_{wc} & \mbox{critical water saturation} & P_{d}^{b} & \mbox{satt distribution coefficient between water phase and} \\ \mu_{w} & \mbox{water viscosity} & \mbox{reservoir rock} \\ S_{org} & \mbox{residual gas oil saturation} & P_{b}^{b} & \mbox{initial bubble point pressure} \\ M & \mbox{mobility ratio} & D_{m} & \mbox{molecular diffusion coefficient} \\ S_{gc} & \mbox{critical gas saturation} & \theta & \mbox{theta} (\mbox{contact angle}) \\ \lambda & \mbox{mobility ratio} & T & \mbox{formation tortuosity} \\ S_{oi} & \mbox{initial oil saturation} & B_{g} & \mbox{gas formation factor} \\ \gamma & \mbox{transmissivity} & P & \mbox{pressure} \\ k & \mbox{permeability} & B_{o} & \mbox{oil formation factor} \\ \psi & \mbox{potential} & g & \mbox{gravity constant} \\ k_{r\beta} & \mbox{plase } \beta \mbox{relative permeability} & B_{\mu} & \mbox{water formation factor} \\ P_{g} & \mbox{water relative permeability} & B_{\mu} & \mbox{pase } \beta \mbox{formation factor} \\ P_{g} & \mbox{gas gas} & \mbox{contact} & P_{b}^{b} \\ k_{ro} & \mbox{oil relative permeability} & B_{\mu} & \mbox{potential} \\ g & \mbox{gas} & \mbox{gas gas} & \mbox{C}_{w} & \mbox{water relative permeability} \\ P_{V} & \mbox{pore volume} & B_{\mu}^{b} & \mbox{potential} \\ g & \mbox{gas} & \mbox{gas} & \mbox{Gravity} & \mbox{gas} & \mbox{gas} & \mbox{motent} & \mbox{gas} \\ k_{ro} & \mbox{oil relative permeability} & \mbox{gas} & \mbox{Gravity} & \mbox{gas} & gas$	$S_{gr}$	residual gas saturation	u	Darcy velocity
	$\mu_{\beta}$	phase B viscosity	$P_{cow}$	water oil capillary pressure
$\begin{array}{cccc} \mu_o & \mbox{oil viscosity} & P_g & \mbox{bubble point pressure} \\ S_{wc} & \mbox{critical water saturation} & K_d & \mbox{salt distribution coefficient between water phase and} \\ \mu_w & \mbox{water viscosity} & \mbox{reservoir rock} \\ S_{org} & \mbox{residual gas oil saturation} & P_b^b & \mbox{initial bubble point pressure} \\ M & \mbox{mobility ratio} & D_m & \mbox{molecular diffusion coefficient} \\ S_{gc} & \mbox{critical gas saturation} & \theta & \mbox{theta} & \mbox{control} & \mbox{critical sas saturation} & \\ \lambda & \mbox{mobility ratio} & \tau & \mbox{formation factor} \\ \gamma & \mbox{transmissivity} & B_o & \mbox{oil formation factor} \\ \gamma & \mbox{pressure} & B_g & \mbox{gas formation factor} \\ \gamma & \mbox{pressure} & \mbox{model} & B_g & \mbox{gas formation factor} \\ \psi & \mbox{potential} & g & \mbox{gravity constant} \\ k_{r\rho} & \mbox{plase $\beta$ relative permeability} & B_{\phi} & \mbox{motential factor} \\ pm & \mbox{parts permittion} & d & \mbox{surface depth} \\ k_{rg} & \mbox{gas relative permeability} & B_{\phi} & \mbox{motential factor} \\ P_V & \mbox{potential} & g & \mbox{potential} & \mbox{formation factor} \\ P_V & \mbox{potential} & g & \mbox{potential} & \mbox{formation factor} \\ P_V & \mbox{potential} & g & \mbox{potential} & \mbox{formation factor} \\ P_V & \mbox{potential} & \mbox{formation factor} & P_b^b \\ k_{ro} & \mbox{oil relative permeability} & \mbox{formation factor} & P_b^b \\ k_{ro} & \mbox{oil relative permeability} & \mbox{formation factor} & \mbox{formation factor} \\ R_{ro}^{\text{swox}} & \mbox{oil relative permeability at critical water saturation} & \mbox{formation factor} \\ R_{ro} & \mbox{oil relative permeability at critical water saturation} & \mbox{formation factor} \\ R_{ro}^{\text{swox}} & \mbox{oil relative permeability at critical water saturation} & \mbox{formation factor} \\ R_{ro}^{\text{swox}} & \mbox{oil relative permeability in 2-phase oil-water system} \\ \end{array}$	Sor	residual oil saturation	q	flowrate
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$k_{ro}^{wo}$ oil relative permeability in 2-phase oil-water system	0	oil	$B_{\beta}$	phase $\beta$ formation factor
	$k_{ro}^{wo}$	oil relative permeability in 2-phase oil-water system		

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<sup>2+</sup> 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)<sub>2</sub>, 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; Download English Version:

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