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A comprehensive review of low salinity/engineered water injections and their applications in sandstone and carbonate rocks

Emad W. Al-Shalabi [a,*], Kamy Sepehrnoori [b]

[a] The Petroleum Institute, United Arab Emirates
[b] The University of Texas at Austin, United States

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ABSTRACT

The low salinity/engineered water injection techniques (LSWI/EWI) have become one of the most important research topics in the oil industry because of their possible advantages for improving oil recovery compared to conventional seawater injection. Researchers have proposed several mechanisms for the LSWI/EWI process in the literature; however, there is no consensus on a single main mechanism for the low salinity effect on oil recovery. Because of the latter, there are few models for LSWI/EWI and especially for carbonates due to their heterogeneity and complexity. In this paper, we present a comprehensive state-of-the-art review on low salinity/engineered water injection for both sandstones and carbonates. This review includes descriptions of underlying mechanisms, spontaneous imbibition and coreflood laboratory work, field-scale pilots, numerical and modeling work, implementation, comparison between sandstones and carbonates, other LSWI/EWI applications, and desalination methods. List of recommendations and conclusions are provided based on this vast literature review and our experiences. This paper can be used as a guide for starting or implementing laboratory- and field-scale projects on low salinity/engineered water injections.

1. Introduction

One of the emerging improved oil recovery (IOR) techniques for wettability alteration in carbonate reservoirs is low salinity water injection (LSWI). The popularity of this technique is due to its high efficiency in displacing light to medium gravity crude oils, ease of injection into oil-bearing formations, availability and affordability of water, and lower capital and operating costs involved, which leads to favorable economics compared to other IOR/EOR methods. The only concern with this technique is water sourcing and water disposal.

The low salinity water injection IOR technique is also known in the literature as LoSal™ by BP, Smart WaterFlood by Saudi Aramco, Designer Waterflood by Shell, and Advanced Ion Management (AIM℠) by ExxonMobil. Several studies have been conducted on low salinity water injection at laboratory-scale and to a limited extent at field-scale. Most studies have confirmed a positive response to low salinity injection, which is translated into additional oil recovery in both secondary and tertiary injection modes. Wettability alteration is believed to be the main reason behind additional oil recovery due to low salinity water injection; however, some other mechanisms were suggested, such as dissolution and fine migration processes. Nevertheless, work is progressing on understanding the chemical interactions between crude oil/brine/rock (COBR) in the system.

Few LSWI modeling studies have been performed so far especially on carbonate rocks compared to sandstone rocks. One of the reasons for this reluctance to investigate the effect of low salinity water injection on carbonate rocks is the extensive research done on sandstone rocks, which concluded that the presence of clay is the main reason for wettability alteration. Moreover, the complex chemical interactions between COBR and the heterogeneity of carbonate rocks make it difficult to predict the extent of additional oil recovery as a result of LSWI. Other reasons involve the mystery of the chemical mechanism behind the oil increase with low salinity injection and the discrepancy in some of the published results regarding the effect of low salinity compared to the seawater injection effect.

Dang et al. (2013a) presented a concise review of the current understanding of LSWI mechanisms, modeling and numerical simulation, LSWI pilot tests, and Hybrid LSWI projects with focus on sandstone rocks. Moreover, Sheng (2014) provided a review on low salinity water injection in sandstones including history of LSWI, laboratory and field observations, mechanisms, and simulation work. This paper is mainly a comprehensive summary of the work performed so far in the area of low salinity/engineered water injections (LSWI/EWI) and their applications in both sandstones

* Corresponding author.

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Nomenclature

Symbols

a	constant, inflection point from curve fitting
a_1, a_2	Langmuir adsorption parameters
C_a	mass fraction of salt component in aqueous phase
C_r	adsorption isotherm of salt onto rock
e	constant, hill slope from curve fitting
e_{ij}	exponent between i and j phases
e_{owmax}	maximum oil–water exponent
e_{ow}^{LS}	oil–water exponent when S_{or} becomes constant
F	scaling factor
I_s	total/stoichiometric ionic strength of solution
k	formation permeability
k_{rl}^{ow}	oil-wet phase relative permeability
k_{rl}^{ww}	water-wet phase relative permeability
k_{rl}^{*}	phase endpoint relative permeability
k_{ro}	oil relative permeability
k_{ro}^{*HS}	oil endpoint for seawater cycle
k_{ro}^{*LS}	oil endpoint when S_{or} becomes constant
k_{rw}	water relative permeability
N_T	trapping number
n_l	phase Corey's exponent
n_o	oil Corey's exponent
n_{omax}	maximum typical oil Corey's exponent
N_T	trapping number
n_w	water Corey's exponent
P_c	capillary pressure, critical pressure
P_{cow}	oil–water capillary pressure
S_l	phase saturation
S_{lr}	phase residual saturation
S_{nl}	phase normalized saturation
S_o	oil saturation
S_{OB}	oil bank saturation
S_{orw}	waterflood residual oil saturation
S_{or}^{HS}	residual oil saturation for seawater cycle
S_{or}^{LS}	minimum residual oil saturation by LSWI
S_{wf}	water shock front saturation
T_l	phase trapping parameter

Greek letters

β_{Ca}	absorbed calcium cation
β_{Mg}	absorbed magnesium cation
τ^*	parameter includes heterogeneity and initial oil saturation effects
ω	scaling factor
ωS	scaling factor for residual oil saturation
λ_{rl}	phase relative mobility
θ	contact angle, scaling factor
θ^{HS}	contact angle for seawater cycle
θ^{LS}	contact angle when S_{or} becomes constant
μ	chemical potential
σ	interfacial tension
ρ	phase density

Subscripts/Superscripts

$_{high}$	high trapping number
$_{HS}$	high salinity water
$_{i}$	initial
low	low trapping number
LS	low salinity water
o	oil
OW	oil-wet
w	water
WW	water-wet

Abbreviations

CEC	Cation Exchange Capacity
CGI	Continuous Gas Injection
CWI	Carbonated Water Injection
DoE	Design of Experiment
EOR	Enhanced Oil Recovery
EWI	Engineered Water Injection
IFT	Interfacial Tension
IOR	Improved Oil Recovery
LSWAG	Low Salinity Water Alternating Gas
LSWI	Low Salinity Water Injection
MED	Multi-Effect Distillation
MIE	Multi-Ion Exchange
MMP	Minimum Miscibility Pressure
MSF	Multi-Stage Flash Distillation
MVC	Mechanical Vapor Compression
NF	Nano-Filtration
NMR	Nuclear Magnetic Resonance
OOIC	Original Oil in Core
OOIP	Original Oil in Place
PV	Pore Volume
PZC	Point of Zero Charge
RO	Reverse Osmosis
RSM	Response Surface Methodology
SRB	Sulfate-Reducing Bacteria
SWAG	Simultaneous Water Alternating Gas
SWCTT	Single Well Chemical Tracer Test
TCD	Thermo-Compression Distillation
TDS	Total Dissolved Solids
UTCHEM	University of Texas Chemical Simulator
UTCOMP	University of Texas Compositional Simulator
WAG	Water Alternating Gas

and carbonates. In the context of this paper, we refer to the process of diluting the injected water as low salinity water injection (LSWI); however, hardening or softening of the injected water is referred to as engineered water injection (EWI). LSWI has been applied for both sandstones and carbonates with more emphasis on sandstones, whereas EWI has mostly been conducted for carbonates. The different applications of LSWI/EWI are also discussed in this paper including conformance control and the combination of LSWI/EWI along with each of surfactants, polymers, and carbon dioxide (CO_2). This paper includes a detailed description of each of the following: effect of LSWI/EWI on sandstone and carbonate rocks, proposed chemical mechanisms for sandstone and carbonate rocks, comparison of both rocks, modeling of LSWI/EWI, other applications of LSWI/EWI, and LSWI/EWI desalination methods.

2. Effect of LSWI/EWI on sandstone rocks

This section includes the LSWI/EWI effect on sandstone rocks at both laboratory-scale and field-scale, and the mechanisms