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Review article

Evidence, mechanisms and improved understanding of controlled salinity waterflooding part 1: Sandstones ☆

M.D. Jackson [a,*], J. Vinogradov [a,b], G. Hamon [c], M. Chamerois [c]

[a] Department of Earth Science and Engineering, Imperial College London, UK
[b] School of Engineering, University of Aberdeen, UK[1]
[c] TOTAL Research, Pau, France

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ABSTRACT

It is widely accepted that oil recovery during waterflooding can be improved by modifying the composition of the injected brine, typically by lowering the total salinity to less than 5000 ppm. Numerous laboratory experiments and field tests, in both clastic and carbonate rock samples and reservoirs, have demonstrated this 'low salinity effect' (LSE). However, despite a plethora of studies and data, the LSE remains poorly understood. Evidence to support the widely held view that improved recovery is conditional on the presence of clay minerals in sandstones, multivalent ions in the formation brine, and significant dilution of the injection brine, is surprisingly scarce. Moreover, there is no method to determine the optimum injection brine composition for a given crude-oil-brine-rock (COBR) system. Many studies have reported the successful application of controlled salinity water injection. However, many others (and more unpublished) observed no benefit, and the available data are often inconsistent and contradictory.

This review collects and summarizes the available data for the first time and discusses the pore- to mineral-surface-scale mechanisms that have been proposed to explain the LSE. Based on this, it outlines an integrated experimental programme that could be used to identify the optimal injection brine composition for a given COBR system. The available evidence suggests that the LSE is real, and is caused by one or more pore- to mineral-surface-scale mechanism(s) which facilitate improved oil recovery at the core- to reservoir-scale. These mechanisms occur at COBR interfaces, and are multi-ion exchange (MIE), local increase in pH (ΔpH) and double layer expansion (DLE). However, the available evidence is not sufficient to unambiguously identify which, if any, of these mechanisms are essential. Other proposed mechanisms, such as clay swelling and fines migration, formation of natural surfactants at elevated pH, reduction in oil/brine interfacial tension, and increased solubility of polar oil compounds in brine, may occur in some cases but do not appear to be necessary to observe improved oil recovery. Understanding is hampered by a lack of common experimental conditions across length-scales. Core-scale measurements are often obtained at reservoir conditions of pressure, temperature, brine salinity and crude oil composition. In contrast, pore- and mineral-surface-scale measurements such as atomic force or scanning electron microscopy, contact angle and wetting surface, adsorption and adhesion, are often obtained at laboratory temperature and pressure, lower brine salinity and simplified crude composition. These contrasting experimental conditions may explain the contradictory data obtained to date.

A common feature of all three proposed mechanisms for the LSE is that they lead to changes in zeta potential at mineral surfaces, either through changes in mineral surface charge (MIE, ΔpH) or changes in the thickness of the double layer (DLE). Thus they change the magnitude of the electrostatic forces acting between mineral surfaces and polar organic species. Experiments that can probe this effect at conditions appropriate to reservoir displacements, whilst also measuring oil recovery, oil and brine composition and pH, and (if possible) the *in-situ* distribution of the fluids, are required to understand the LSE and predict the optimum injection brine composition for a given COBR system.

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* Corresponding author.

E-mail address: m.d.jackson@imperial.ac.uk (M.D. Jackson).

[1] Present address.

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1. Introduction

It is now widely accepted that oil recovery during secondary or tertiary waterflooding can be improved by modifying the composition of the injected brine, typically by lowering the total salinity to less than 5000 ppm (for comparison, seawater salinity is c. 35,000 ppm and many formation brines have salinities in excess of 200,000 ppm; e.g. [15]). Numerous laboratory experiments and field tests, in both clastic and carbonate rock samples and reservoirs, have demonstrated this 'low salinity effect' (LSE) (e.g. [58,59,62,73,92,93,108,109,113,115,116,122–124,126]). Modification of injected brine composition was first suggested as an IOR method in clastic reservoirs in the late 1950s by Martin [69] and again in the 1960s by Bernard [18]. However, the approach did not gain traction until the 1990s and 2000s, when Morrow and co-workers published a series of papers that demonstrated the LSE in corefloođing experiments on outcrop and reservoir sandstones [50,75,106–109,119,127]. Shortly after, BP published the results of a 'log-inject-log' field trial which showed that injection of low salinity brine (<3000 ppm) in a clastic reservoir reduced the residual oil saturation relative to the injection of seawater or high salinity formation brine (c. 220,000 ppm; [115]).

Since these early studies, a large and increasing number of papers have been published on controlled salinity waterflooding. These have demonstrated its successful application in other laboratory experiments and field trials (e.g. [6,34,58,59,65,78]; see, for example, Fig. 1a and b) and in carbonate as well as clastic rocks and reservoirs (e.g. [121–126]. Increases in oil recovery of up to 35% compared to re-injection of formation brine have been observed in laboratory coreflooding experiments (e.g. [13,62,73]), and field tests have demonstrated decreases in residual oil saturation of 50% compared to conventional water injection (e.g. [93,115]). Moreover, there has been increasing focus on the collection of laboratory data to explain the LSE, including contact angles (e.g. [7]), oil-brine interfacial tension (e.g. [45]), coreflood effluent brine composition and pH (e.g. [58]), zeta potential of mineral surfaces (e.g. [77]), cation-exchange-capacity (CEC) (e.g. [79]), adhesion maps (e.g. [22,25]), adsorption studies (e.g. [13]), and imaging of mineral surfaces at a variety of length scales (e.g. [17,41,117]). However, despite this plethora of new studies and data, the LSE remains poorly understood. Many published studies have reported the successful application of controlled salinity water injection (e.g. [58,59,62,73,92,93,108,109,113,115,116]), but there are also many other published experiments (and many more unpublished), in which no benefit was observed (e.g. [6,19,34,77,81,84,86,94,95,99,127]; see, for example, Fig. 1c and d). Moreover, many studies report data that support a particular hypothesis but contradict, or are inconsistent with, the results of