Journal of Petroleum Science and Engineering 137 (2016) 157–171

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

journal homepage: www.elsevier.com/locate/petrol

Numerical modeling of combined low salinity water and carbon dioxide in carbonate cores

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

[a] Petroleum Engineering Department, The Petroleum Institute, Abu Dhabi, UAE
[b] Petroleum and Geosystems Engineering, The University of Texas at Austin, Austin, TX, USA

ARTICLE INFO

Article history:
Received 24 June 2015
Received in revised form
10 November 2015
Accepted 25 November 2015
Available online 27 November 2015

Keywords:
Low salinity water injection (LSWI)
Combined effect of LSWI and CO_2
Fractional flow analysis
Tertiary recovery factor
Utilization factor

ABSTRACT

This paper investigates the combined effect of injecting low salinity water (LSWI) and carbon dioxide (CO_2) on oil recovery from carbonate cores. The combined effect of LSWI and CO_2 injection on oil recovery was predicted by performing several 1D simulations using measured reservoir rock and fluid data. These simulations included the effect of salinity on both miscible and immiscible continuous gas injection (CGI), simultaneous water-alternating-gas (SWAG), constant water-alternating-gas (WAG), and tapered (WAG). For SWAG and constant and tapered WAG, both seawater and its dilutions were simulated. CO_2 was injected above its minimum miscibility pressure. Baker's three-phase relative permeability model was modified to account for the effect of salinity on the water/oil relative permeability.

The results show that SWAG, whether using seawater or its dilutions, outperformed all other tertiary injection modes in terms of oil recovery. Moreover, the SWAG process has both the highest tertiary recovery factor (TRF) and the lowest utilization factor (UF). This study highlights the advantage of using low salinity water along with miscible CO_2. The miscible CO_2 displaces the residual oil saturation whereas the low salinity water boosts the production rate by increasing the oil relative permeability through wettability alteration towards more a water-wet state. The latter finding was supported by comparing our simulations with the two corefloods reported by Chandrasekhar and Mohanty (2014). These corefloods were conducted in SWAG tertiary mode using seawater and its dilutions. Fractional flow analysis shows that SWAG with low salinity water requires less injected solvent compared to SWAG with seawater and miscible CGI.

1. Introduction and background

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. The low salinity water injection includes diluting, hardening or softening of the injected water. In this paper, the focus is on diluting the injected water. CO_2 miscible flooding is a well established commercial enhanced oil recovery (EOR) method to recover light crude oils from carbonate formations. The purpose of this study was to explore the combined benefits of these two processes.

* Corresponding author.
E-mail addresses: emalshalabi@pi.ac.ae (E.W. Al-Shalabi), kamys@mail.utexas.edu (K. Sepehrnoori), gpope@mail.utexas.edu (G. Pope).

http://dx.doi.org/10.1016/j.petrol.2015.11.021
0920-4105/

1.1. Low salinity water injection (LSWI)

The low salinity water injection IOR technique is also known in the industry as LoSal™ by BP, Smart WaterFlood by Saudi Aramco, Designer Waterflood by Shell, and Advanced Ion Management (AIM℠) by ExxonMobil. Several laboratory studies have been performed using low salinity water injection in carbonates (Hognesen et al., 2005; Webb et al., 2005; Zhang et al., 2007; Gupta et al., 2011; Yousef et al., 2011, 2012a; Zhang and Sarma, 2012; Chandrasekhar and Mohanty, 2013). 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. The first ever LSWI field application in carbonate reservoirs was reported by Yousef et al. (2012b). Two single well chemical tracer tests (SWCTT) were applied in an Upper Jurassic carbonate reservoir using a diluted version of Qurayyah seawater. The tests resulted in about 7 saturation units reduction in the residual oil beyond conventional seawater injection. The results obtained were in match with their previous experimental work

Nomenclature

a	constant, inflection point from curve fitting
e	constant, hill slope for 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_{wJ}	water fractional flow at the injection end
HS	high salinity water
LS	low salinity water
k_{rl}^{*}	phase endpoint relative permeability
k_{ro}^{*HS}	oil endpoint for seawater cycle
k_{ro}^{*LS}	oil endpoint when S_{or} becomes constant
ms	optimum solvent amount
NMR	nuclear magnetic resonance
S_{lr}	phase residual saturation
S_{or}^{HS}	residual oil saturation for seawater cycle
S_{or}^{LS}	minimum residual oil saturation by LSWI
t_{Ds}	solvent+water slug size
λ_T	total mobility
ω	scaling factor
θ^{HS}	contact angle for seawater cycle
θ^{LS}	contact angle when S_{or} becomes constant

which is encouraging to plan a multi-well demonstration pilot.

The mechanism controlling the LSWI effect on oil recovery from carbonate rocks is less complicated compared to sandstone rocks. Most of the conducted research agrees on wettability alteration as the main contributor to LSWI effect on carbonate rocks (Standnes and Austad, 2000; Bagci et al., 2001; Strand et al., 2003; Hognesen et al., 2005; Zhang et al., 2006; Puntervold et al., 2007; Austad et al., 2008; Gupta et al., 2011; Yousef et al., 2011; Chandrasekhar and Mohanty, 2013). Wettability alteration in carbonate rocks using modified-ion water can be achieved by injecting water containing SO_4^{2-} and either Ca^{2+} or Mg^{2+} or both of them in the presence of high temperatures (>90 °C) (Zhang et al., 2006). Yousef et al. (2012a) demonstrated that wettability alteration is the reason behind LSWI through nuclear magnetic resonance (NMR), contact angle measurement, and zeta potential studies. Nevertheless, work is progressing on understanding the chemical interactions between crude oil/brine/rock (COBR) in the system.

1.2. Miscible/immiscible gas injection

Miscible gas flooding is classified into first-contact miscible (FCM) or multi-contact miscible (MCM) depending on the manner in which miscibility is developed in-situ. In FCM, the reservoir hydrocarbon is miscible with the injection gas in any proportion (no interface between the fluids), so piston-like displacement occurs. Usually, FCM displacement requires very high pressures that are usually not obtainable. On the other hand, in MCM the miscibility is developed in-situ by repeated contacts between the injection gas and the reservoir fluid through which composition changes from multi-contacts and mass transfer between reservoir oil and injected fluid (Benham et al., 1960; Stalkup, 1983; Zick, 1986; Johns et al., 1993; Green and Willhite, 1998).

Gas flooding processes can be classified as immiscible, FCM or MCM based on where the composition of the injection gas falls on the ternary diagram with respect to the critical tie-line and the reservoir oil composition. MCM can be further classified into vaporizing gas drive, condensing gas drive or a combination of both. Combination of both vaporizing and condensing gas drives is the most commonly observed in reality. The minimum miscibility pressure (MMP) is the minimum pressure required for the injected gas to achieve miscibility with the reservoir fluid at reservoir temperature and for a given injection gas composition. The simulation of this process requires a compositional simulator when the fluid properties depend on pressure and composition. Examples of miscible gas injection are carbon dioxide, enriched hydrocarbon gas, and depletion of volatile oil or gas-condensate reservoirs (Khan, 1992).

1.3. WAG/SWAG injection

Miscible or near miscible CO_2 flooding results in high microscopic displacement efficiency, however, the high mobility of CO_2, reservoir heterogeneity, and gravity segregation reduce the reservoir sweep efficiency. Hence, mobility control is needed to achieve high total oil recovery (Fjelde and Asen, 2010). Water alternating gas (WAG) is one of the commonly used mobility control techniques upon which alternating cycles of gas followed by water are injected. A comprehensive classification of the WAG process includes: MWAG (miscible), IWAG (immiscible), HWAG (hybrid), Tapered WAG, SWAG (simultaneous) and SSWAG (selective) (Christensen et al., 1998; Al-Mamari et al., 2007; Skauge and Dale, 2007). MWAG and IWAG are cyclic WAG processes upon which the injected gas is miscible and immiscible, respectively. Hybrid WAG is a process in which a large slug of gas is injected in the reservoir followed by a number of small slugs of water and gas. In tapered WAG, there is an increase in the WAG ratio as the flood progresses. In SWAG, water and gas are mixed at the surface and then injected at the same time in the reservoir through a single injection well. Nevertheless, when the water and gas are injected separately using a dual completion injector, without mixing water and gas at surface, then the process is referred as selective simultaneously water alternating gas (SSWAG) (Hustad et al., 2002; Quijada, 2005). Several factors may affect CO_2–WAG including reservoir heterogeneity, fluid properties, miscibility condition, rock wettability, and WAG parameters such as water–gas slug size, timing of injection and WAG ratio (Jiang et al., 2010).

1.4. Other application of LSWI

Ayirala et al. (2010) reported the advantages of using low salinity water as base water to prepare polymer solution for polymerflooding. One of these advantages is the lower capital and operational costs compared to using seawater as base water for preparing polymer solutions. This is related to polymer facilities as the use of low salinity water reduces the need for more chemicals to meet a certain viscosity requirement. It should be noted that additional desalination unit is needed for the case of low salinity water; however, the adjustment in polymer facilities might compensate for this cost. Moreover, a higher oil recovery can be obtained by improving the microscopic displacement efficiency using low salinity waterflooding and macroscopic sweep efficiency using polymerflooding. The combination of low salinity waterflooding and polymer is very attractive as one third or less of polymer is required for polymer floods, added to the 5-times reduction in chemical cost per barrel of oil recovered (Mohammadi and Jerauld, 2012).

Spildo et al. (2012) investigated the effect of combining low