Journal of Natural Gas Science and Engineering 35 (2016) 237–258

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

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

# Evaluation of $CO_2$ Low Salinity Water-Alternating-Gas for enhanced oil recovery

Cuong Dang [a,*], Long Nghiem [a], Ngoc Nguyen [b], Zhangxin Chen [b], Quoc Nguyen [c]

[a] Computer Modelling Group Ltd., Canada
[b] Department of Chemical & Petroleum Engineering, University of Calgary, Canada
[c] Department of Petroleum & Geosystems Engineering, The University of Texas at Austin, United States

ARTICLE INFO

*Article history:*
Received 19 May 2016
Received in revised form
5 July 2016
Accepted 2 August 2016
Available online 4 August 2016

*Keywords:*
Low Salinity Water-Alternating-Gas
Low salinity water flooding
WAG
Enhanced oil recovery

ABSTRACT

Low Salinity Waterflooding (LSW) is an emerging attractive enhanced oil recovery (EOR) method because of its oil recovery performance and relatively simple, environmentally friendly implementation, when compared with conventional high salinity waterflooding and EOR approaches. More importantly, another advantage of LSW is that it can be integrated with other EOR methods (in hybrid LSW processes), i.e. chemical or miscible gas flooding. The merits of combining LSW with $CO_2$ injection is investigated in this paper, and a novel EOR method, Low Salinity Water Alternating $CO_2$ ($CO_2$ LSWAG), is proposed. $CO_2$ LSWAG injection promotes the synergy of the mechanisms underlying these methods which further enhances oil recovery and overcomes the late production problems frequently encountered in conventional WAG. $CO_2$ LSWAG has been evaluated in both one-dimensional and full-field scale with positive results compared with conventional high salinity WAG.

To investigate the advantages of $CO_2$ LSWAG, a comprehensive ion exchange model associated with geochemical processes has been implemented and coupled to the multi-phase multi-component flow equations in an equation-of-state compositional simulator. 1D simulation of different $CO_2$ LSWAG schemes are first conducted to understand the combined effects of solubility of $CO_2$ in brine, dissolution of carbonate minerals, ion exchange, and wettability alteration. $CO_2$ LSWAG performance is then evaluated on a field scale through an integrated workflow that includes geological modeling, multi-phase multi component reservoir flow modeling and process optimization. The simulation results indicate that $CO_2$ LSWAG has the highest oil recovery compared to conventional high salinity waterflood, high salinity WAG, continuous $CO_2$ flooding, and low salinity waterflood. A number of geological realizations are generated to assess the geological uncertainty effect, in particular clay distribution uncertainties, on $CO_2$ LSWAG efficiency. $CO_2$ LSWAG injection strategies are optimized by identifying key WAG parameters. Finally, $CO_2$ LSWAG is evaluated in the full field scale for a North Sea reservoir and the simulation results shows that $CO_2$ LSWAG yields about 4.5% incremental OOIP compared to the conventional high salinity WAG.

The proposed workflow demonstrates the synergy between $CO_2$ WAG and LSW. Built in a robust reservoir simulator, it serves as a powerful tool for screening, design, optimization, and uncertainty assessment of the process. $CO_2$ LSWAG is a promising EOR technique as it not only combines the benefits of $CO_2$ injection and low salinity water floods but also promotes the synergy between these processes through the interactions between geochemical reactions associated with $CO_2$ injection, ion exchange process, and wettability alteration. This paper demonstrates the merits of this process through modeling, optimization and uncertainty assessment.



## 1. Introduction

Low Salinity Waterflooding (LSW) has received increasing attention in the oil industry and is currently identified as an important EOR technique as it shows more advantages than conventional chemical EOR methods in terms of chemical costs,

* Corresponding author.
*E-mail address:* cuong.dang@cmgl.ca (C. Dang).

http://dx.doi.org/10.1016/j.jngse.2016.08.018

environmental impact, and field process implementation. The modification of the injected brine composition could improve the oil recovery factor of conventional waterflooding up to 38% (Webb et al., 2004), leading to a new concept of optimal injection brine composition for waterflooding. Other than using high salinity reservoir water, extensive laboratory experiments (Tang and Morrow, 1997; Morrow et al., 1998; Tang and Morrow, 1999a, 1999b; Zhang and Morrow, 2006; Kumar et al., 2010; Loahardjo et al., 2010) and pilot tests (McGuire et al., 2005; Lager et al., 2008; Skrettingland et al., 2010; Thyne and Gamage, 2011) have confirmed the advantages of using low salinity brine as an injected fluid on the oil recovery for both secondary and tertiary modes.

Although the benefits of LSW have been realized, the mechanism for incremental oil recovery by LSW is still a topic for open discussions. Several mechanisms have been proposed during the last two decades including fines migration, wettability alteration, multi-component ionic exchange (MIE), saponification, pH modification, and electrical double layer effects. Dang et al. (2013b) provided a critical review and discussion of these mechanisms. Among the proposed hypotheses, wettability alteration towards increased water wetness during LSW is the widely accepted cause for enhanced oil recovery. The effects of low salinity brine on wettability modifications have been reported by many authors (Jadhunandan and Morrow, 1995; Tang and Morrow, 1999a; Drummond and Israelachvili, 2002, 2004; Vledder et al., 2010; Zekri et al., 2011). It has been experimentally found that the low salinity brine has a significant effect on the shape and the end points of the relative permeability curves (Webb et al., 2004; Kulkarni and Rao, 2005; Rivet, 2009; Fjelde et al., 2012), resulting in a lower water relative permeability and higher oil relative permeability. The mechanisms of wettability alteration due to ion exchange and geochemical reactions have been successfully implemented in a compositional simulator for modeling of LSW (Dang et al., 2013a). Excellent agreements between simulation results and important measurements from coreflood experiments and pilot observations were obtained with this modeling approach.

LSW can be considered as secondary and tertiary recovery or can be combined with other EOR approaches such as chemical flooding (e.g., polymer or surfactant), referred as hybrid LSW in the literature. The first attempts at implementing hybrid LSW EOR was to combine LSW with low-tension surfactant flooding. This is an economically attractive hybrid EOR process since using surfactant under low salinity conditions improves surfactant solubility and reduces adsorption and retention, resulting in improved economic performance (Kozaki, 2012; Dang et al., 2014). Alagic and Skauge (2010) reported that significant incremental oil recovery was obtained for a Low Salinity Surfactant (LS-S) flood when the core was pre-flushed with low-salinity brine compared with an LS-S flood in a high-salinity environment. LS-S in aged Berea sandstone cores lowered residual oil saturations down to around 0.05. It was concluded that surfactant stayed in the aqueous phase and microemulsion was successfully formed under the low-salinity conditions, instead of moving over to the oil phase and being trapped there under increased salinity conditions. This phenomenon could well be explained by Winsor type I, II, and III phase behavior in chemical flooding. Along with low-tension surfactant flooding, polymer flooding is also an attractive EOR approach that has been widely investigated in laboratory and field scales. Based on a number of coreflood experiments, Kozaki (2012) concluded that the use of low-salinity polymer flooding has significant benefits because of considerably lower amount of required polymer for a target viscosity. Additionally, low-salinity polymer flooding can also increase oil recovery by lowering residual oil saturation and achieving faster oil recovery by wettability alteration. These observations have been confirmed by Mohammadi and Jerauld (2012) based on numerical simulation. The simulation results show that low-salinity polymer flooding gave about 5% incremental oil recovery over high-salinity polymer flooding, and a five times reduction in chemical costs per barrel of oil recovered can be realized when polymer is added to low-salinity brine.

Not limited to chemical flooding, a new concept of hybrid LSW has been explored by combining LSW with $CO_2$ Water-Alternating-$CO_2$ (WAG) under miscible injection conditions and this concept is referred to as $CO_2$ LSWAG Kulkarni and Rao (2005) conducted miscible and immiscible WAG with varying brine composition on Berea sandstone cores. They reported a decrease in oil recovery with decreasing the salinity of the injected water due to an increase in the solubility of $CO_2$ in brine. The effect of injection brine salinity on $CO_2$-WAG performance in the tertiary mode was investigated by Jiang et al. (2010) on Berea sandstone cores by changing the salinity of the injected brine up to 32,000 ppm. The coreflooding experiments were run at 60 °C and at a pressure of 20% above the minimum miscibility pressure (MMP) to ensure miscible $CO_2$ flooding. The results revealed that the WAG recovery increases with increasing the salinity of the injection brine and this was explained due to a salting out effect, as the solubility of $CO_2$ in water decreases with increasing the salinity. This allows more $CO_2$ available for oil displacement resulting in higher oil recovery. However, it is important to note that the sandstone core samples used in these investigations were strongly water-wet with very low clay content. This is an unfavorable condition for achieving wettability alteration, which is the key factor to obtain the benefit of LSW (Rivet, 2009; Dang et al., 2015b). Fjelde and Asen (2010) investigated wettability alteration during water flooding and $CO_2$ flooding on reservoir rocks from the North Sea at different temperatures (50 and 130 °C). The experimental work started with formation water as a first phase, followed by sea water as a second phase and finally a cycle of sea water $CO_2$ WAG as a third phase. The results showed that wettability alteration towards more water-wet was observed after the WAG slug resulted in residual oil saturation between 3 and 5%. One of the promising investigations in this area was conducted by Zolfaghari et al. (2013). They reported, based a series of coreflood experiments under conditions favorable for LSW application, that $CO_2$ LSWAG gave additional oil recovery of up to 18% OOIP. Interesting findings from their results are that $CO_2$ LSWAG is also highly effective for heavy oil and the ultimate recovery by LSW is even higher than that by $CO_2$ HSWAG. These positive results encourage the extension of LSW and $CO_2$ LSWAG, currently limited to application in light/medium oil reservoirs, into heavy oil reservoirs.

Recently, Ramanathan et al. (2015) conducted an investigation of the effect of salinity on the waterflooding as well as water alternating $CO_2$ injection process through six coreflood experiments. They found that wettability alteration towards a more water-wet state was the cause of improved oil recovery by LSW and the solubility of $CO_2$ due to water composition is very important on the performance of $CO_2$ LSWAG. Fines migration was also observed during low salinity brine alternating $CO_2$ injection process. Teklu et al. (2016) observed that the higher solubility of $CO_2$ in low salinity water as compared to high salinity water is the main reason for the improvement in residual oil mobilization as compared to conventional WAG and higher $CO_2$ solubility in brine can lead to stronger carbonated water in situ to alter wettability and reduce IFT and viscosity further. Al-Shalabi investigated the potential of combining LSW and carbon dioxide in carbonate reservoir using numerical simulation and they concluded that this hybrid process is promising as $CO_2$ controls the residual oil saturation whereas LSWI boosts the oil production rate through increasing oil relative permeability by wettability alteration (Al-Shalabi et al., 2016).

Despite significant growing interest in $CO_2$ LSWAG, most of previous evaluations for this process have been done with