Fuel 178 (2016) 1–9

Contents lists available at ScienceDirect

Fuel

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

# The influence of spreading coefficient on carbonated water alternating gas injection in a heavy crude oil

Masoud Riazi [a,*], Abdolah Golkari [b]

[a] Enhanced Oil Recovery (EOR) Research Centre, School of Chemical and Petroleum Engineering, Shiraz University, Shiraz, Iran
[b] Department of Chemical Engineering, School of Chemical and Petroleum Engineering, Shiraz University, Shiraz, Iran

A R T I C L E  I N F O

*Article history:*
Received 9 May 2015
Received in revised form 4 March 2016
Accepted 8 March 2016
Available online 17 March 2016

*Keywords:*
Carbonated water alternating gas (CWAG)
Oil swelling
Pendant drop method
Interfacial tension (IFT)
Spreading coefficient (SC)

A B S T R A C T

The interfacial properties change strongly with temperature and pressure that could influence the displacement of fluids in porous media. The main objective of this study was to measure interfacial tension (IFT) of the binary systems of brine/crude oil/carbon dioxide ($CO_2$) and carbonated brine/crude oil/$CO_2$ at two temperatures and different pressure conditions. Spreading coefficient (SC), which is determined from IFT data, is an important parameter in enhanced oil recovery (EOR) methods, which are based on three phase systems. The spreading or non-spreading (the oil creates to form an immobile half sphere) oil on the water–gas interface is a key factor on determining residual oil saturation during water alternating gas (WAG) injection process. In this work, experimental results on oil swelling and interfacial tension of crude oil, brine/carbonated brine and carbon dioxide systems at the pressure range of 2.76–13.79 MPa and two temperatures of 40 °C and 50 °C is presented. Afterwards, by estimating spreading coefficient of the mentioned systems an optimum condition for the enhanced oil recovery (EOR)-WAG process is proposed.

The results indicate that, the equilibrium IFT data of the carbonated brine–crude oil system is lower compared to that of the brine–crude oil system at the same conditions. The interfacial tension of the carbonated brine–crude oil system decreases significantly at higher pressures. In addition to IFT reduction due to the presence of $CO_2$ in water, oil swelling was also observed. In this experimental work, the dynamic oil swelling was monitored as a function of time. The IFT data of the above systems were also used to estimate the spreading coefficient as a function of pressure at both temperature conditions. The estimated spreading coefficient data for the brine/crude oil/$CO_2$ and carbonated brine/crude oil/$CO_2$ systems, indicates that the presence of $CO_2$ in the brine phase, makes the spreading coefficient positive, while this parameter in the brine/oil/$CO_2$ system is negative. This means that oil would be spread on the water phase during carbonated water alternating $CO_2$ injection that consequently could further enhance oil recovery.



## 1. Introduction

Different stages of oil recovery are categorized into three periods of primary, secondary and tertiary. Primary production arises from natural reservoir pressure. Recovery factor of this stage depends to the reservoir rock properties, the oil viscosity, and the reservoir pressure. When oil production rate during primary stage is not economical, secondary recovery stage starts. At the secondary recovery stage, water or gas is injected into the reservoir to keep and build up the pressure. However, the recovery factor after primary and secondary stages is about 30–50%. It means that about two third of the original oil in place is trapped and remains unrecovered due to the balance of capillary and viscous forces. To produce the trapped oil phase enhanced oil recovery (EOR) techniques are suggested and applied [1,2]. In this regard, extensive laboratory studies and field applications of water alternating gas injection (WAGI), cyclic injection of carbonated water (CW) and $CO_2$, carbon dioxide-EOR processes to investigate the potential of carbonated water injection as an injection method for improved oil recovery and $CO_2$ storage have been performed [3–8]. Storing carbon dioxide underground is being considered as a promising sequestration technology for mitigating greenhouse gas emissions [9–11]. In $CO_2$-EOR and $CO_2$ storage processes, the interfacial tension phenomenon could strongly affect fluids (i.e. crude oil, reservoir brine and $CO_2$) distribution, and flow behavior within

* Corresponding author. Tel.: +98 71 36133714; fax: +98 71 36474602.
*E-mail address:* mriazi@shirazu.ac.ir (M. Riazi).

http://dx.doi.org/10.1016/j.fuel.2016.03.021
0016-2361/

reservoir at high pressure conditions [12,13]. Two main mechanisms of oil recovery that occur in the carbonated water injection (CWI) process include swelling and coalescence of trapped oil and the oil viscosity reduction as a result of diffusion and segregation of $CO_2$ from carbonated water into oil [5]. The interfacial tension reduction can also be the other positive effect of CWI compared to water injection (WI) process in the oil reservoir [14]. Furthermore, the interfacial properties of the crude oil, brine and $CO_2$ system vary significantly after $CO_2$ injection at reservoir conditions. Thus, it is of basic and operational importance to investigate the interfacial tension phenomenon carefully in the crude oil–brine–$CO_2$ systems at high pressure and high temperature conditions. Among several presented techniques for measuring the interfacial tension (IFT), the pendant/rising drop method is probably one of the best techniques for estimating the IFT at high pressure and temperature conditions (i.e. at reservoir conditions). For the first time this technique was used by Jennings Jr to estimate the interfacial tension by taking images a pendant drop and then estimating the drop diameters [15–17]. Moreover, when the density difference of the two phases is very small (e.g. about 0.01 g $cm^{-3}$), then the pendant/rising drop method cannot be applied to determine the IFT [17]. Recently, this technique has been significantly developed and is widely used to estimate the IFT data. Different research groups used this technique to determine IFT values for different fluid systems: the IFTs of the n-paraffin-$CO_2$ systems [18–23], the systems of synthetic oil–$CO_2$, the systems of live crude oil–$CO_2$ [24,25], the systems of crude oil–$CO_2$ [14,26,27], the systems of n-paraffin-water/brine [28,29], the systems of crude oil–brine [14,30,31] and the water–$CO_2$ systems [14,32,33]. Recently, the axisymmetric drop shape analysis (ADSA) technique for the pendant drop method is known as a new advanced method for measuring the interfacial tension. ADSA technique was initially developed by several researchers [34], and was further improved by another team [35]. With compared to the other methods, accuracy of the ADSA technique for the pendant/rising drop method has been approved for the interfacial tension estimation [36,37]. In this work, by estimating spreading coefficient of the crude oil–brine (carbonated brine)-$CO_2$ systems an optimum condition for the EOR-WAG/CWAG processes is determined.

Riazi et al. using micromodel experiments investigated the effect of carbonated water injection (CWI) instead of water injection (WI) prior to carbon dioxide injection ($CO_2$I) on oil displacement mechanisms and recovery. According to their results carbonated water makes the Glassy micromodel more water wet. Moreover, they observed that $CO_2$ flooding performances after WI and CWI are different. That was, the injection of carbon dioxide after CWI recovered more oil compared to that after WI [5,38]. The proposed mechanism for the higher performance of $CO_2$I in the former process was due to the existence of a continuous oil film between the water and the displacing $CO_2$ phases.

The main objective of the present work is to describe how the brine/carbonated brine (CB)-$CO_2$ IFT, brine/carbonated brine–oil IFT, $CO_2$–oil IFT data can be used on optimization of CWAG process. To study the effect of pressure on IFT of oil, gas and brine systems, the experimental results were utilized. Finally, based on the experimental results, the ability of the oil phase to spread on water in the presence of $CO_2$ gas was investigated. These results were also applied to discover an optimum flooding pressure conditions for trapped oil saturation assessment after water and gas displacement process of an Iranian oil reservoir. Spreading coefficient (SC) is defined for water–oil–gas system, as the ability of the oil phase to spread as a thin film between the water–gas phases. This phenomenon (i.e., spreading of crude oil phase) occurs in water-wet rocks when spreading coefficient is positive. Spreading coefficient (SC) is estimated by the following equation:

$$SC = \gamma_{CO2-W} - (\gamma_{O-W} + \gamma_{CO2-O}) \tag{1}$$

where SC is the spreading coefficient, $\gamma_{CO2-W}$, $\gamma_{CO2-O}$ and $\gamma_{O-W}$ are IFT of $CO_2$/water, $CO_2$/oil and oil/water systems, respectively.

Spreading coefficient is usually used to describe the physically and chemically interactions between different fluids. It can be either positive or negative depending on the composition of fluids in-place and the reservoir pressure and temperature conditions [39]. Spreading coefficient would also determine the nature of distribution of the water, oil and gas within the reservoir rock pores. Thus, it can be a key factor in gas/water/oil relative flow behaviors and determining the additional oil recovery [40,41]. The oil recovery and efficiency of an EOR process depends on the spreading coefficient and wettability of the porous medium. In this work, spreading coefficient is estimated for a three phase system.

Oren et al. [39,42] using the three fluids of air, refined oil and distilled water investigated the spreading coefficient in porous rocks with different wettability conditions. They concluded that in a water-wet system, oil recovery for the SC > 0 was significantly higher compared to that for the case when the SC < 0; whereas the oil-wet system displayed an opposite trend.

In addition, Vizika and Lombard [43] using gravity drainage experiments studied the spreading and non-spreading conditions in three systems of water-wet, oil-wet and fractionally-wet. Their results indicated that the highest oil recoveries were obtained for positive value of SC and water-wet or fractionally-wet conditions. The lowest oil recovery was obtained for negative values of SC and the water-wet system.

In another experimental work, Sharma and Filoco [44] studied the effect of spreading coefficient on the residual oil saturation. They performed the drainage tests with samples the air, brine (NaCl) and decane/dodecene on the water-wet Berea sandstone core. A small amount of iso-butanol was added to the brine phase aiming to change the initial spreading coefficient from positive to negative. Their results indicated that the positive spreading coefficient (SC = 5.5) results in a very low remaining oil saturation compared to the negative SC (SC = −4.1).

When the SC is positive, the oil phase will spread between the water and gas phases. Hence, oil would easily flow within the porous medium during the course of immiscible gas injection. The film continuity of oil favors the hydraulic stability of the oil phase that results on more oil recovery and hence reduces the trapped oil saturation [45].

In the case of the negative spreading coefficient value, oil would be trapped within the pore space as a lens of static oil on the water phase. Since, the oil does not have the ability to spread under negative spreading coefficient conditions in a water wet rock sample. Therefore, the water phase may flow and bypass the oil and finally, a higher trapped oil saturation be left behind [46]. The precise IFT estimation is also important for evaluating the oil production performance of a fractured reservoir [47]. One of the most important oil production mechanisms in fractured reservoirs, is gravity drainage [43,48,49]. The distribution and displacement of reservoir fluids in the pores are mainly affected by capillary forces, which depend on interfacial properties of the rock and fluids (i.e. the rock wettability and fluids IFT) [46,50].

Amin and Smith [46] measured the IFT of three systems of methane against the pentane, heptane and n-decane by applying the pendant drop method at different pressure and temperature conditions. Using IFT measurements, they reported the spreading coefficient (SC) values for a crude oil/brine/gas system at reservoir conditions. They also observed a negative SC value at pressures higher than 20.68 MPa. Thus, they suggested that operating pressure for EOR process should be performed below 20.68 MPa, because the spreading coefficient values are positive at pressures lower than this pressure. In this experimental work, the IFT