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Full Length Article

Simulation of carbonated water injection coreflood experiments: An insight into the wettability effect

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HIGHLIGHTS

- A CWI coreflood experiment performed in a mixed-wet core is studied mathematically.
- Compared to CWI in a water-wet core, a different simulation procedure is suggested.
- The contribution of both wettability alteration and oil swilling mechanisms is discussed.

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ABSTRACT

In this paper, our previously developed model (simulator) has been used to simulate and study a different CWI coreflood experiment from the literature performed in a mixed-wet sandstone core. The developed model that was based on mass transfer kinetics had been used before to simulate a coreflood experiment performed in a water-wet sandstone rock. In this paper, a different procedure has been applied for the simulation of CWI in the mixed-wet core. That is, in contrast to the water-wet coreflood test where only mass transfer parameter was tuned, here, both mass transfer parameter and relative permeability curves have been obtained through a history matching experiment applying our genetic algorithm (GA) based optimization program. Furthermore, using the simulation results, it has been observed that in addition to oil swelling and contrary to the water-wet core, wettability alteration is also an important recovery mechanism for the mixed-wet core. The potential of CO_2 storage during the mixed-wet CWI coreflood experiment has also been investigated. The results obtained in this paper can help to crosscheck and verify the performance of the developed simulator and also to explore its generic capability. Moreover, the results of this paper give an insight into different recovery mechanisms contributing during CWI coreflood experiments.

1. Introduction

Carbonated water (CW) injection is a CO_2-EOR method where CO_2 is used efficiently. In carbonated water injection (CWI) technique and compared to conventional water injection (WI), water will be saturated with CO_2 before injecting into oil reservoirs. Upon contact of CW with oil in the reservoir, CO_2 starts migrating to the oil phase due to its higher solubility in hydrocarbons compared to water, which results in a higher oil recovery factor. During CWI, CO_2 stays dissolved in oil and water phases and not as a free phase; therefore, it gives a better sweep efficiency compared to the pure CO_2 injection strategy. Moreover, contrary to the pure CO_2 injection strategy, CWI needs less amount of CO_2 making it an attractive CO_2-EOR strategy for offshore fields, where the supply of CO_2 is limited. Furthermore, through CWI and at the end of the injection period, some amount of CO_2 (as a greenhouse gas) is stored in the reservoir securely as is dissolved in remaining oil and water [1–4]. CWI has been investigated experimentally and mathematically in the literature. Experimental study of CWI has mainly been focused on flooding tests including cores [4–9] and sand packed setups [10,11]. Direct visualization of flow during CWI using high-pressure transparent micro-model setup (high pressure Hele-Shaw) has also been considered in the literature [4,12,13]. All the reported experiments show an increased recovery factor obtained by CW over conventional WI with some CO_2 stored in the system at the end of the experiments. The experiments could help to understand the mechanisms involved during CWI. When CO_2 migrates to the oil phase during CWI, it increases the oil volume (oil swelling) and decreases its viscosity, and reduces IFT of water-oil system all resulting in a better recovery factor [4,5,12–14]. However the

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Nomenclature

ω_o^o	mass fraction of the oil component in the oil-CO_2 mixture
$\omega_o^{CO_2}$	mass fraction of the CO_2 component in the oil-CO_2 mixture
$\omega_w^{CO_2}$	mass fraction of the CO_2 component in the water-CO_2 mixture
ω_w^w	mass fraction of the water component in the water-CO_2 mixture
$C_o^{CO_2}$	CO_2 concentration in the oil-CO_2 mixture (g/cm^3)
$C_w^{CO_2}$	CO_2 concentration in the water-CO_2 mixture (g/cm^3)
$C_o^{CO_2^*}$	CO_2 concentration (g/cm^3) in oil phase at the equilibrium state
$C_w^{CO_2^*}$	CO_2 concentration (g/cm^3) in water phase at the equilibrium state
k_{eq}	distribution coefficient, here is 9.6 [1]
MTC	pseudo mass transfer coefficient (1/sec)
p	phase pressure (atm)
s	phase saturation
k	absolute permeability (mD)
φ	porosity
μ_o	viscosity of the oil-CO_2 mixture at test conditions (cP)
μ_w	viscosity of the water-CO_2 mixture at test conditions (cP)
μ_{water}	viscosity of pure water at test conditions (cP)
p_{ce}	entry capillary pressure (atm)
λ	pore-size distribution index
Pcmax	maximum Pc (i.e. Pc at connate water saturation)
β	an unknown parameter in Pc correlation.
K	($k_m \times a$) with 'k_m' is the overall mass transfer coefficient (cm/sec) and 'a' is the specific interfacial area (1/cm)
N_c	capillary number
u_{df}	velocity of displacing fluid, here is carbonated water (m/sec)
μ_{df}	viscosity of displacing fluid, here is carbonated water (kg/m sec)
σ	carbonated water-decane interfacial tension, here is 20E−3 (N/m) [29]

wettability of rock also affects the efficiency of CWI process. Sohrabi et al. [5] performed a series of CWI coreflood experiments in a water-wet and a mixed-wet aged core. They observed that under the same conditions, the recovery obtained for the aged core was higher. The change of wettability of the rock in the presence of CO_2 and specifically by carbonated water is reported in the literature. Yang et al. [15] experimentally measured the contact angle of a crude oil-carbonate rock –carbonated brine system at high pressure and temperatures. A change in contact angle (around 20°) from oil-wet toward intermediate-wet (neutral-wet) due to the presence of CO_2 in the system was observed quickly (in less than 10 min). Seyyedi et al. [16] performed a series of contact angle measurements to determine the wettability of three different minerals (substrates) of quartz (the main mineral of sandstone rocks), mica, and calcite (the main mineral of carbonate rocks) in the presence of a crude oil and carbonated brine at reservoir conditions. In addition to clean substrates, the substrates were also aged in the same crude oil to measure the contact angle of aged minerals as well. The aged quartz showed a contact angle change from 76° to 61° (natural-wet toward water-wet) and for the aged calcite a contact angle change from 144° to 97° was observed (oil-wet toward neutral-wet) due to CO_2 dissolution in brine. For the unaged minerals, a small change in contact angle was observed (around 5° or less). To provide more support to the idea of wettability change during CWI, Seyyedi and Sohrabi [17] performed a series of spontaneous imbibition tests at reservoir conditions using aged and unaged sandstone and carbonate rock samples. No spontaneous imbibition was observed for aged sandstone and carbonate samples when brine was used whereas carbonated water could imbibe into the rock sample. Al-Mutairi et al. [18] measured the wettability of an aged carbonate rock sample under 500 psi pressure and 70 °C. They observed that the contact angle was changed quickly (in less than 1 h) from 101° to 83° when it was contacted by carbonated water. Wettability alteration by carbonated water has also been observed in micro-model setup. Based on some observations in a micro-model setup, Sohrabi et al. [5] realized that the shape of oil ganglia trapped were more rounded after CWI compared to those after WI. They expressed that this difference in shape of oil blobs indicates that the surface of micro-model has become more water-wet after CWI. All these studies show that the carbonated water can change the wettability of rock surfaces specifically the oil-wet surfaces to neutral-wet surfaces or neutral-wet surfaces to more water-wet surfaces, but it has a minimal effect on water-wet or strong water-wet surfaces. As compared to experimental study, mathematical modeling and simulation of CWI process have not been studied much in the literature. De Nevers [19] presented an analytical model based on the Buckley–Leveret theory to predict the CWI performance. Ramesh and Dixon [20] presented a numerical black-oil based model to predict the performance of Carbone Dioxide (CO_2) flooding and CWI into heterogeneous oil reservoirs. Chang et al. [21] developed a three-dimensional, three-phase compositional simulator to include the impact of CO_2 solubility in water during CO_2 injection. In the compositional model mentioned above, the assumption of instantaneous equilibrium was applied. This assumption implies that in a simulation grid block, distribution of CO_2 between water and oil happens instantly to reach an immediate equilibrium state. Kechut et al. [6] used ECLIPSE300 (E300) commercial software to simulate some available CWI coreflood experiments. They argued that E300 cannot properly simulate this process due to intrinsic assumption of instantaneous equilibrium made by E300 which is not valid for CWI coreflood experiments. As mentioned in the literature [22], this assumption can lead to large errors where for example there are short contact times for mass transfer process (laboratory displacement in cores) or large diffusion patterns are available for components to diffuse through them (field scale) and moreover, if there is slow diffusion velocities due to large viscosity of resident fluids. Accordingly, we previously developed a new compositional simulator (model) for simulating CWI process based on mass transfer kinetics where the assumption of instantaneous equilibrium was relaxed [1]. We used the developed model for simulation of a CWI coreflood experiment carried out in an unaged water-wet core. In this article we will use the developed model for simulation of a different CWI coreflood experiment from the literature carried out in an aged mixed-wet core. The simulation results are interpreted to discover different recovery mechanisms of CWI in water-wet and mixed-wet cores. That is, the main goal here is to explore the role of rock wettability and wettability alteration in the performance of CWI process by considering the experimental data of two cores with different wettabilities. The structure of this paper is as follows: first, a summary of the developed model is presented, next, the results of coreflood experiments are presented