Investigation of Water Flooding and Carbonated Water Injection (CWI) in a Fractured Porous Media

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This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Vienna, Austria, 27 August – 1 September 2017

ABSTRACT

Carbonated water injection (CWI) for enhanced oil recovery (EOR) has been investigated in several studies. Vertical and horizontal displacements are affected by heterogeneity especially fractures in porous media. This work is part of a comprehensive study on how the fracture geometry affects the performance of carbonated water injection in presence of gravity. It is motivated from previous work where we observed increased recovery using CWI compared to water flooding in homogenous media.

In this study, a fractured porous medium was fabricated in a glass micromodel for medium pressure (ambient to 1000 psi (6.89 MPa) experiments. Simple water flooding and CWI were performed in a fractured medium with vertical fractures at 305 psi (2.1 MPa) and 69.8°F (21°C). This study analyzes the effects of CWI on sweep efficiency and pore scale recovery. The results show that CWI is more effective in fracture oil recovery, trapped oil extraction than simple water flooding in vertically oriented fractured porous media. CWI displaces oil in the entire micromodel as well as around fractures, whereas in water flooding, water is not being able to distribute evenly in porous media and recover oil in narrow pores, throats and fractures. We observed better sweep efficiency in the lower part of the porous media when vertical fractures were present. The mechanistic study of macroscale displacement revealed that reduced oil viscosity controls the oil displacement in fractures. Fracture-matrix interaction was enhanced under CWI. Fractures were observed to conduct the oil extensively. The effect of gravity was verified by performing CWI injection in vertically oriented fractured micromodel. A quantitative analysis confirmed higher performance of CWI than water flooding in the presence of gravity by an additional 10.8% compared to water flooding.

INTRODUCTION

Gas injection is a potential method to improve sweep efficiency [Cotter 1962, Holm and Josendal 1974]. The challenge with every CO_2-based EOR process is to increase both micro and macro scale displacement efficiencies. The oil swelling and partial miscibility phenomenon still plays an important role in an immiscible CO_2 injection where sufficient CO_2 transfers to the oil phase swelling the oil helping reconnect immobilized oil ganglia. Reducing the oil viscosity and increasing oil swelling are two active mechanisms in CO_2

injection. [Khatib et al. 1981]. The solubility of CO_2 in both water and oil phases is a function of both pressure and temperature although it is a stronger function of pressure.. CO_2 is more soluble in oil than other gases [Klins and Farouq 1982]. The main challenge for a successful CO_2 injection process is related to the CO_2 density and viscosity, which cause poor volumetric sweep efficiency [Wellington and Vinegar 1985]. In general, the high viscosity contrast between the gas and oil results in highly unfavorable mobility, and the high density difference between the gas and the oil results in gravity segregation. Consequently, CO_2 injection often results in poor sweep efficiency [Green and Wilhite 1998]. Poor sweep efficiency is common in a fractured porous medium. Low displacing fluid viscosity can cause the fluid to flow through high-permeability zones bypassing oil in neighbouring matrix zones. Fractures cause premature breakthrough and an unstable frontal displacement which leads to poor overall recovery [Laroche et al. 1999]. In gas injection processes, gas and oil interactions are promoted by fractures more than in conventional reservoirs. However, high gas mobility compared to water and oil cause by-passed oil and gravity override [Van Dijkum and Walker 1991]. A challenge with continuous CO_2 injection, water alternating gas injection (WAG), and simultaneous WAG (SWAG) is that the sweep efficiency is still poor [Kulkarni and Rao 2005; Rangel-German and Kovsec, 2006]. Solvent injection in homogeneous and especially heterogeneous porous media results in very low residual oil saturation [Er 2007]. CWI is suggested as a possible alternative method.

Several studies have been performed on the efficiency of CWI since 1951 [Martin 1951; Perez et al. 1992; Dong et al. 2011]. CWI is an alternative injection method that requires less CO_2 compared to continuous CO_2 injection. Hence, this process is attractive for reservoirs with limited access to CO_2 such as remote offshore fields. Riazi et al. [2011] performed a series of homogeneous micromodel studies at 2000 psia (13.7 MPa) and 100 °F (38°C). They recorded 6-8% additional oil recovery for secondary and tertiary CWI compared to water flooding. Sohrabi et al. [2012] investigated the effect of CWI on core scale oil recovery where they achieved an additional 24% recovery. Mosavat and Torabi [2014, 2017] conducted a series of homogeneous micromodel and sand-pack studies. They believed that the main oil trapping mechanism was wettability trapping. Compared to water flooding, secondary and tertiary CWI recovered 9.4% and 7.3% additional oil, respectively. We previously [Mahdavi et al. 2016] investigated the effect of CWI in a homogeneous glass micromodel at 305 psia (2.1 MPa) and 69.8 °F (21°C) in the presence of gravity. The effect of gravity was observed in both water flooding and secondary CWI. Better oil redistribution and fewer by-passed oil zones were detected in CWI compared to water flooding in the presence of gravity. Residual oil approached 50% for CWI compared to 64% in water flooding. Seyyedi et al. [2017] conducted a series of tests: micromodel, slimtube and coreflooding experiments using live oil at 2500 psia (17 MPa) and 100 °F (38°C). The compositional analysis on each contact period showed that a new gas phase is formed plus the live oil (CH_4 + stock tank oil) and carbonated phase. At the early stage, the new phase has less CH_4 and CO_2 content; later the contact made the new gas phase rich in CO_2 resulting in 24% additional oil recovery compared to water flooding. According to the literature there is no reported comparative studies of CWI in heterogeneous fractured porous media in the presence of gravity. In this study, we examine CWI in heterogeneous media in the presence of gravity.

EXPERIMENTAL PROCEDURE

Fluids Characterization- The fluids in this study are oil (29.8 °API) from offshore Canada, deionized water (DI) and pure CO_2 supplied by Praxair (99.8% purity). We measured and calculated all the physical properties at 305 psia (2.1 MPa) and 21°C (69.8 °F). The viscosity of the oil (6.8 cP) and DI (0.997 cP) was measured using a Cambridge VISCOlab PVT high pressure viscometer. The density of the oil (0.877 g/cm^3) and DI water (0.997 g/cm^3) was measured using an Anton Paar densitometer. A high-resolution camera (Canon EOS 6D, 100 mm focal length) was used to take pictures of the CWI process and the images were analyzed using in-house image analysis software. To differentiate between the fluids, the water was dyed blue using methylene blue while the CW was colorless, and the oil was dark brown. The carbonated water was prepared by mixing CO_2 with deionized water for 48 hours to reach the equilibrium. The solubility of CO_2, in DI was calculated using CMG-WINPROP^{TM}. The calculated solubility of CO_2 in oil and DI water was $0.021\ {}^{\mathrm{g\,CO_2}}/_{\mathrm{kg\ oil}}$ and $0.014\ {}^{\mathrm{g\,CO_2}}/_{\mathrm{kg\ water}}$, respectively.

Porous Medium Characterization- A heterogeneous micromodel (20 cm × 3.5 cm) with fractures was designed and fabricated. A close-up image of the fully oil saturated micromodel is shown in Figure 1. Experiments including water flooding and secondary CWI were performed in both horizontal (laying flat, no gravity) and vertical (on edge, with gravity) orientations.

Matrix and Fracture Characterization- A matrix pattern was prepared using a thin section of a sandstone rock sampled from an offshore oil reservoir and drawn in Corel DRAW X7. We etched four vertical fractures perpendicular to fluid flow (Figure 1). The overall length (the vertical distance between top and bottom) and aperture of each fracture is 1.29 and 0.1 cm, respectively. Using image analysis, the porosity of the micromodel was determined to be 38%. The etched depth of the micromodel varied between 60 – 70 μm measured using scanning electron microscopy (SEM). The water steady state permeability was determined to be 400 D for the overall micromodel.

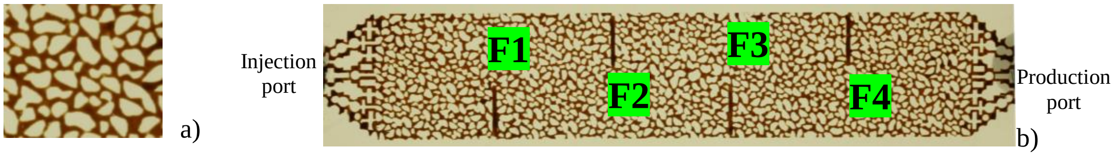


Figure 1: Schematic of fractured micromodel with fractures (denoted F) perpendicular to flow), a) a close-up and b) whole micromodel

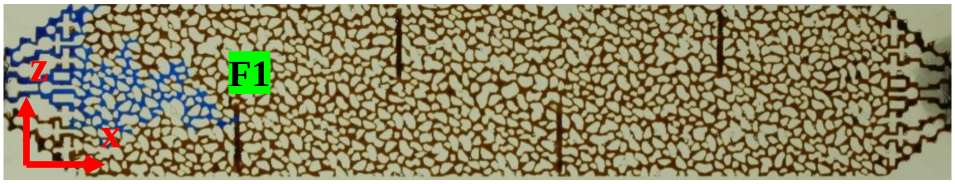
Experimental Procedure-The experimental setup consists of a Quizix 20K pump, accumulators, pressure transducers, and imaging system. Before each test, the micromodel was first cleaned using solvents (i.e. toluene, acetone and water) and dried with air then fully saturated with oil. The experimental conditions were set at a pressure of 305 psi (2.1 MPa) and a temperature of 21°C (69.8 °F). Water or carbonated water (depending on experiment) was injected at a rate of 0.0024 cc/min to satisfy the capillary number in the range of 10^{-7}. Some of the experiments were conducted twice for repeatability.

RESULTS and DISCUSSION

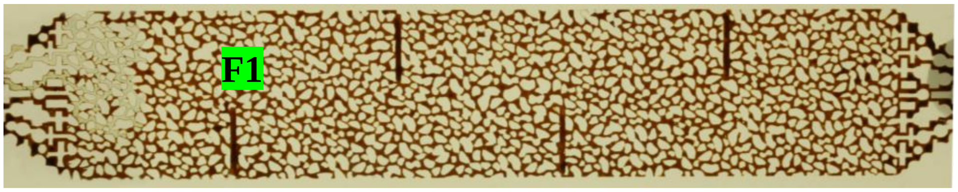
Comparison of WF and CWI with Gravity

The water flooding (WF) and CWI scenarios were conducted in two different orientations: with and without gravity. The displacement pattern, matrix-fracture interaction, residual oil saturation and pore scale phenomena were recorded. Figure 2 shows a series of some of the vertical WF and CWI experiments under gravity effect at different injected pore volumes. Water enters the micromodel (Figure 2a) and then moves downward due to the gravity effect to fill the fracture 1 (F1) whereas, the CW front (z-x direction) moves forward slower than the water front. Moreover, CW is distributed more evenly in z-direction (Figure 2a') than water (Figure 2a). By comparing to the oil displacement pattern in Figures 2b and 2b' at 0.05 PV, it is observed that in proximity to the fracture, the water fingers towards the fracture (F3).

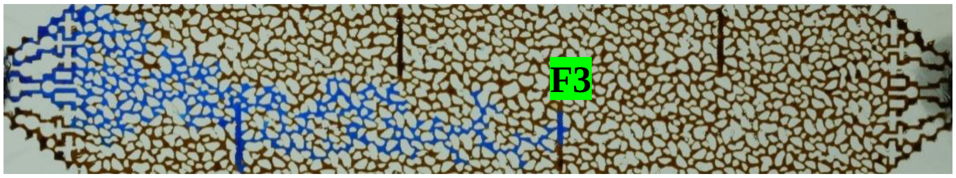
Breakthrough occurred in WF and CWI at 0.24 and 0.37 PV injection, respectively, which is shown in Figure 2c and 2c'. The fluid distribution in the fracture and the matrix was more evenly distributed in CWI than water flooding prior to breakthrough (Figure 2c and 2c'). The oil displacement in the lower part of the micromodel was more complete and homogenous in CWI than WF. Water could reach to the upper fracture F2 (Figure 2c) and displace the oil in the fracture which did not happen in the case of CWI in Figure 2c'. However, comparing the residual oil saturation upstream (to the left) of fracture F2 in Figures 2d and 2d', we observe better sweep efficiency for the carbonated water (CWI) than water (WF) and there was a large by-passed zone behind the fracture F2.



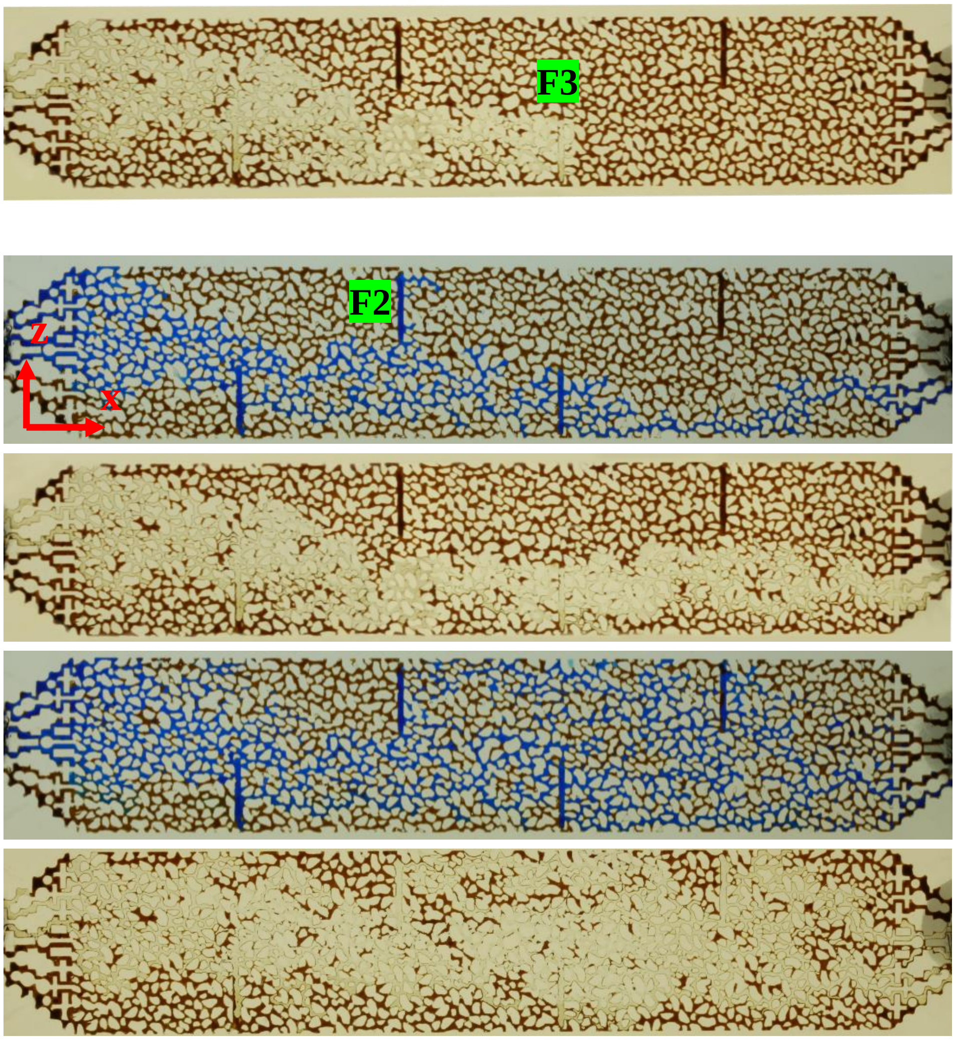
2a) WF-V
9.2% recovery
at 0.05 PV



2a') CWI-V
14.9% recovery
at 0.05 PV



2b) WF-V
22.9% recovery
at 0.17 PV



2b') CWI-V
24.1% recovery
at 0.17 PV

2c) WF-V
25.2% recovery
at 0.24 PV (BT)

2c') CWI-V
38.1% recovery
at 0.37 PV (BT)

2d) WF-V
38.8% recovery
at 7 PV
38.8%

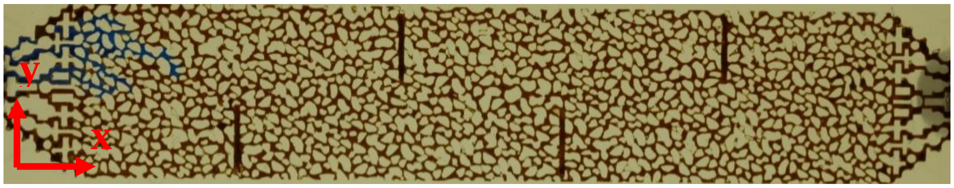
2d') CWI-V
48.9% recovery
at 7 PV

Figure 2: Comparison of WF and CWI in the presence of gravity (vertical orientation)

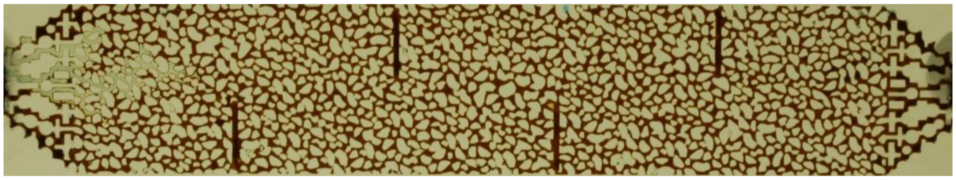
By continuing injection to ~ 7 PV (Figures 2d and 2d'), CWI indicates that the CW phase is able to sweep the remaining oil in the upper fractures and matrix over a large area. The trapped oil in WF is mostly oil banks, especially in the upper part and close to the production port (right side of the figures). In contrast to waterflooding, CWI traps oil mostly in pore spaces. Recovery factor changes 25.2% and 38.1% from breakthrough to 38.6% and 49.7% for water flooding and CWI, respectively (average of two replicates).

Comparison of WF and CWI without Gravity

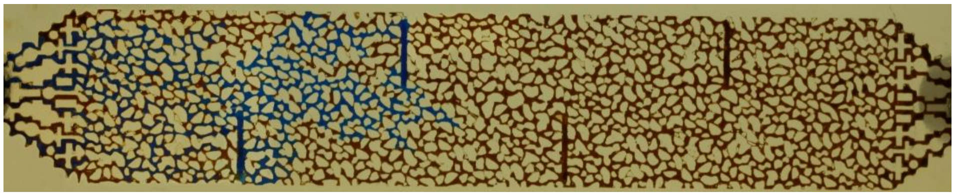
The performance of CWI and WF were examined without the effect of gravity in a fractured micromodel (Figure 3's series). We observed that, initially water and CW have similar displacement patterns (Figures 3a and 3a'). However, water appears to exhibit viscous fingering behaviour more than CWI. In CWI, the CW distribution and displacement patterns among the fractures and matrix are more homogeneous (Figures 3b and 3b') due to the modified mobility of CW. The mobility control is the dominant mechanism in CWI before breakthrough.



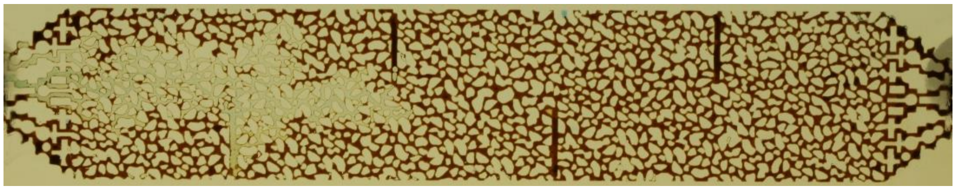
3a) WF-H 3.0% recovery at 0.05 PV



3a') CWI-H 5.4% recovery at 0.05 PV

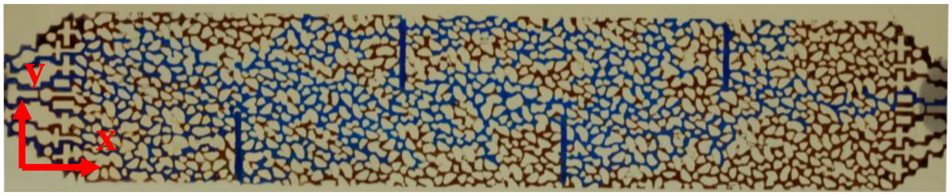


3b) WF-H 14.9% recovery at 0.17 PV

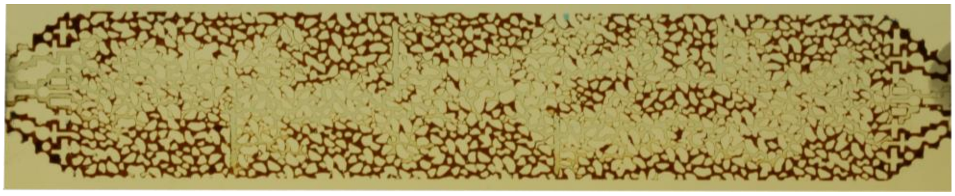


3b') CWI-H 12.9% recovery at 0.17 PV

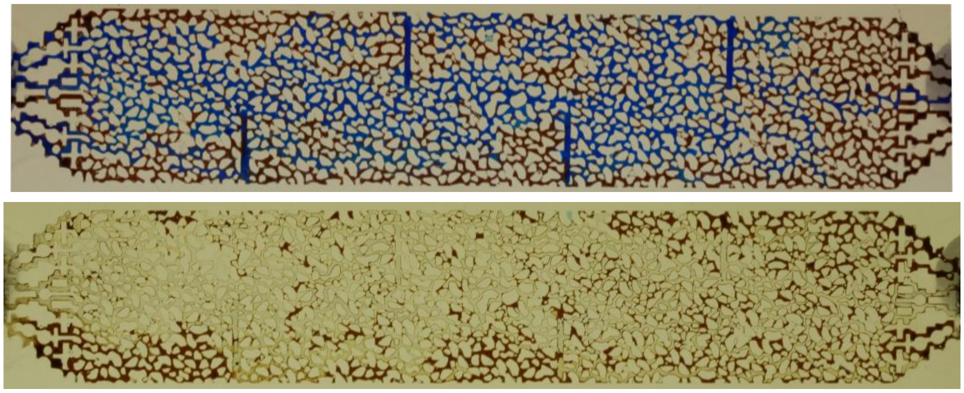
Breakthrough happens in WF and CWI at 0.1 PV and 0.13 PV, respectively. The oil displacement pattern is more homogeneous in CWI than WF. However, there is not much difference in oil recovery in WF and CWI prior to breakthrough (Figures 3c and 3c') due to effect of fractures and flow distribution. The viscous fingering is more pronounced near the production port for WF compared to CWI (Figure 3c and 3c' at right side), i.e. the flood front moves in a more stable manner in the case of CWI.



3c) WF-H 38.6% recovery at 0.35 PV (BT)



3c') CWI-H 40.0% recovery at 0.44 PV (BT)



3d) WF-H
43.7%
recovery at
7 PV

3d') CWI-H
57.0%
recovery at
7 PV

Figure 4: Comparison of WF and CWI without gravity

Overall, CWI has a more effective, stable frontal displacement and pore scale recovery in presence of fractures perpendicular to the flow. After breakthrough, the residual oil decreases more with CWI. At 7 PV (Figures 3d and 3d') it is clear that CWI has better sweep and pore scale recovery efficiency compared to WF.

Fracture Conduction

It was found that fractures (highlighted by the green lines) play an important role in oil displacement in a fractured porous media (Figure 5). It is shown that the fractures play a role in collecting and transporting oil mostly via film flow. Fluid flow moves towards the fractures being more permeable. The water or carbonated water and oil move from matrix pores upstream of the fracture into the fracture and outward into the matrix again downstream of the fracture. The oil from different pores appears to accumulate in the fracture entering the porous matrix again (Figure 5 a-c and Figure 5 d-h).

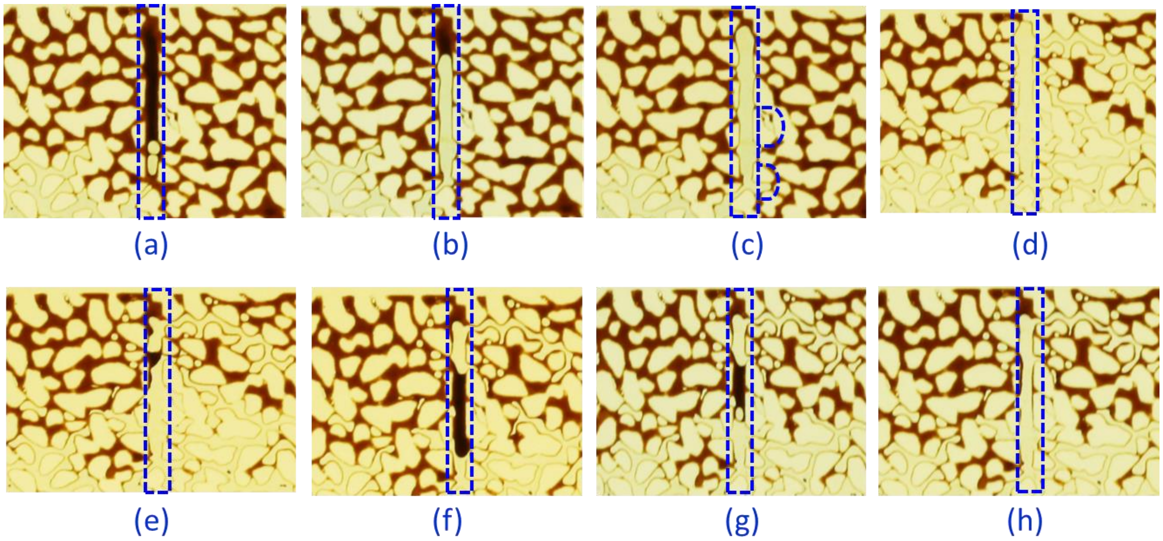


Figure 5: Sequence of fracture oil conduction

Recovery Analysis

Figure 6 shows the recovery factor versus injected pore volume. As shown the higher recovery is achieved when gravity is not present (micromodel is horizontal). Ultimate oil recovery at 7 PV injection was 57.1% for CWI in the horizontal micromodel compared to 43.7% recovery from WF without the effect of gravity. After breakthrough, CWI recovered more oil than WF in the horizontal models (40.0% recovery at breakthrough to 57.1% at 7 PV for CWI and 38.6 % recovery at breakthrough to 43.7% at 7 PV for WF). In the presence of gravity, we see similar phenomena in that recovery at breakthrough is substantially higher for CWI compared to WF.

Recovery from the vertical micromodel with fractures at breakthrough and 7 PV injection is on average 38.6% and 49.7%, respectively using CWI. Waterflooding recovery was 25.2% and 38.8% at breakthrough and 7 PV water injected. Mahdavi and James [2016] reported an average of 15.3% recovery at breakthrough and 52.5% recovery at 7 PV injected for CWI using a homogenous micromodel (no fractures) with similar permeability. The ultimate recovery is similar but there is a large difference in recovery at breakthrough. Water flooding from the vertical homogenous model recovered 25.7% and 36.2% at breakthrough and 7 PV injected, respectively [Mahdavi and James, 2016]. The comparable waterflooding recovery results between the homogenous micromodel and the micromodel with fractures indicates our ability to compare recovery results between the different micromodels. The fractures do not seem to increase sweep efficiency for the water flooding case. What we see is higher recovery at breakthrough using CWI in a fractured micromodel compared to waterflooding and even CWI in a homogeneous micromodel. These differences may be attributed to primarily better vertical sweep efficiency when fractures are present. The transfer of CO_2 from the water to the oil swells the oil and possible developing miscibility may contribute to the increased production observed using CWI compared to WF.

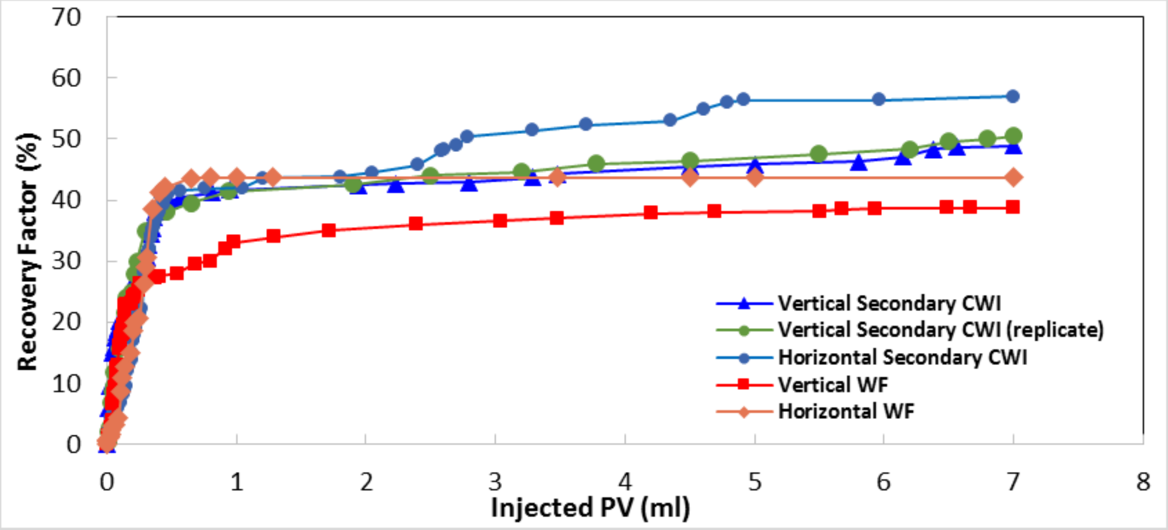


Figure 6: Oil recovery factor in different scenarios as a function of injected pore volume

CONCLUSION

Based on the pore scale fractured micromodel experiments, the effect of gravity was verified in presence of fractures. We observed that vertically oriented fractures aids in the distribution of the carbonated water in the micromodel increasing vertical sweep efficiency. Water flooding exhibited earlier breakthrough compared to CWI under similar conditions. CWI produces more oil after breakthrough. Horizontal carbonated water phase sweeps a larger area and results in less residual oil saturation after breakthrough. Pore scale events such as fracture conduction and oil entrapment were observed in both water flooding and CWI. However, fracture conduction and pore scale sweep efficiency was more pronounced in CWI. It is believed that CO_2 transferred from the water to the oil and partial miscibility may be reasons for better recovery efficiency from carbonated water compared to water alone.

ACKNOWLEDGEMENTS

The authors thank the Hibernia Management and Development Company (HMDC), Chevron Canada, and the Petroleum Research Newfoundland and Labrador (PRNL) for the support without which this work could not have been performed.

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