# Pore Scale Investigation of Carbonated Water Injection with and without Gravity

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## ABSTRACT

In this study, the use of $CO_2$ for carbonated water injection (CWI) in pore network micromodels is investigated. Different scenarios, including water injection, secondary and tertiary CWI were performed under different oil production rates at constant temperature. The injection pressure was kept constant at 305 psi (2.1 MPa) and the production rate varied. The distribution pattern of the carbonated water in the porous media is a function of oil production rate. When the oil production rate is high, the breakthrough happens early and oil recovery is less than when production rates are lower. At a higher oil production rate, the carbonated water phase cannot sweep the oil and will not distribute in different directions of throats in the porous media. These results are analysed with respect to dimensionless analysis. The effect of gravity was verified by performing CWI injection in the presence of gravity. Pore scale events such as trapped oil are observed and seen to be affected by the production rate.

## INTRODUCTION

Secondary recovery techniques such as water or gas flooding help increase production by re-pressurizing the reservoirs but leave much oil trapped in place due to capillarity and/or low sweep efficiency. Enhanced oil recovery techniques can increase recovery by an additional 3-15%. The challenge is to target both pore scale and field scale (vertical and horizontal) displacement efficiency for the specific reservoir characteristics. Many field tests have demonstrated that without the benefit of vertical displacement, water flooding and gas injection operations usually result in low vertical sweep efficiency [8-10]. Water alternating gas (WAG), simultaneous WAG (SWAG) and carbonated water injection (CWI) can address the problem of efficiently recovering oil through combining advantages of both water flooding (bottom layers displacement) and gas injection operations (top layers displacement) [1-3]. $CO_2$ is more soluble in oil than the other gases, so $CO_2$ based EOR processes are more cost effective than the other gas based EOR methods as they can use less amount of $CO_2$ for the same performance. They are also environmentally friendly as they capture $CO_2$ from atmosphere [4,5]. Methods that require less $CO_2$ such as CWI, are more practical in offshore and harsh environments where the only gas/$CO_2$ supply may be $CO_2$ separated from gas cap, solution gas, a nearby gas reservoir and/or flue gas from onboard electrical generation [4,6,7]. Various studies have been conducted to macroscopically and microscopically understand the phenomena behind the solvent injection and displacement. Pore scale interactions in visual porous media have also been studied for CWI and other EOR applications [11-14]. CWI has been found to be effective in recovering oil from complex porous media [14]. Martin [15] studied the effect of CWI on oil recovery using core samples and found a 12% improvement on oil recovery compared to water flooding. Dong et al. (2011) found that CWI recovered more oil compared to water flooding from sand packs and core samples in secondary and tertiary modes. Higher flooding rates gave optimal recovery factor [16]. Sohrabi et al. [18] recorded 24% additional oil recovery during tertiary CWI compared to water flooding in a series of core flooding experiments, and later water breakthrough in CWI than in plain water injection. The effect of CWI on oil recovery at high pressure and temperature has been investigated [14, 17]. Riazi et al. [14] compared CWI with water flooding using horizontal homogeneous micromodel at 2000 psia (13.7 MPa) and 38°C where 41, 47, and 49% recovery for water flooding, tertiary and secondary CWI, respectively. In this research the effect of CWI in vertically oriented micromodel was investigated to understand the performance of CWI on vertical oil displacement and oil distribution using different schemes.

# EXPERIMENTAL DETAILS

The injection of CWI in a pore network micromodel, with and without gravity, was examined using a pressurized micromodel setup shown in Figure 1. The injection pressure was kept constant at 305 psi (2.1 MPa) and 21ºC. The homogeneous (in house etched) glass micromodels (see Table 1) were saturated with oil until no air bubbles were observed. Based on the defined scenario (see Table 3), water flooding, secondary, or tertiary CWI injection began by stabilizing the pressure difference between the inlet and outlet of the micromodel. A high resolution camera (Canon EOS 6D, 100 mm focal length) was used and images were analyzed using in-house image analysis software.

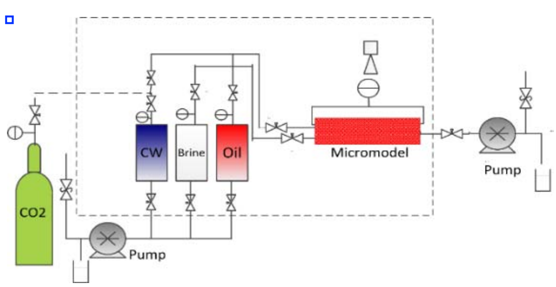



**Figure 1. Schematic of CWI experiment in pressurized micromodel setup**

**Table 1. Micromodel characteristics**

| L (mm) | W (mm) | K (D) | ϕ (%) | Pore diameter (mm) | Throat width (mm) |
|---|---|---|---|---|---|
| 270 | 50.7 | 450 | 30% | 0.650, 0.773, 0.998 | 0.26, 0.33, 0.69 |


**Figure 2. Micromodel**

**Table 2. Fluid properties**

| $\rho_O$ Kg/m$^3$ | $\mu_O$ cP | $\rho_{CW}$ Kg/m$^3$ | $\mu_{CW}$ cP | $\rho_W$ Kg/m$^3$ | $\mu_W$ cP | $\sigma_{(o-w)}$ N/m |
|---|---|---|---|---|---|---|
| 877 | 14.62 | 1015 | 0.95 | 0.997 | 1.0 | 0.029* |

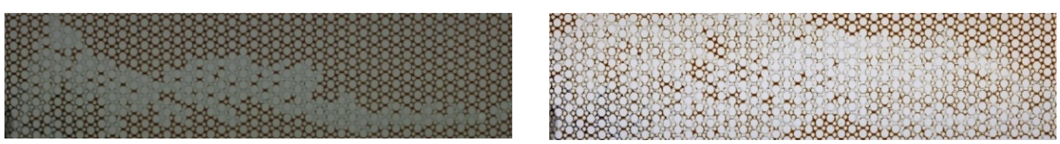
*: The same number for oil/CW was used

$\rho$: density, $\mu$: viscosity, $\sigma$: interfacial tension, $o$: oil, $w$: water, $cw$: carbonated water

The fluids are light oil, deionized water (DI) and pure $CO_2$ supplied by Praxair (99.8% purity). Their properties are given in Table 2. The viscosity of the oil was measured by VISCOlab PVT apparatus, high pressure viscometer at 21 °C and 305 psi. The viscosity and density of water and carbonated water were calculated at experimental condition (21 °C and 305 psi) using HYSYS software. The interfacial tension between oil and water was measured at 21 °C and 305 psi by VINCI IFT 700 apparatus. In order to differentiate between the oil, water, and carbonated water (CW), methylene blue was used to dye the water phase while the CW was colorless in both secondary and tertiary scenarios. The carbonated water was prepared by mixing deionized water and pure $CO_2$ at 21ºC and 220 psi (1.5 MPa) for 48 hours.

## RESULTS AND DISCUSSION

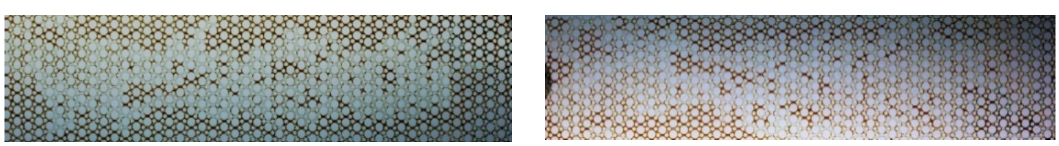
**Vertical vs Horizontal CWI:** The effect of gravity on CWI injection was investigated in horizontally and vertically oriented pore network micromodels. Figure 3 shows water flooding and secondary CWI in both vertically and horizontally oriented micromodels. Please note that 1) injection is from left to right, and 2) horizontal means laid flat on a table (Y-X orientation) while vertical means standing up in landscape orientation (Z-X orientation). Figure 3a-left (and the repeat in Figure 3d-left) shows that gravity causes the carbonated water (CW) to move downward until breakthrough, whereas the CW is distributed more evenly prior to breakthrough in the horizontally oriented micromodel due to the lack of gravity effect (Figure 3b-left). The fluid distribution after 3.2 PV CWI indicates that CW phase is able to sweep the remaining oil over a large area in both vertically and horizontally oriented micromodels (Figure 3a-right/3d-right and 3b-right). However, earlier breakthrough happens in vertically oriented micromodel compared to horizontal one due to effect of gravity. Residual oil saturation in vertically oriented micromodel is decreased gradually after breakthrough, while in the horizontally oriented micromodel it remains almost constant (Figure 4). Residual oil saturation changes 35.5% and 21.7% from breakthrough up to 3.2 PV in vertically and horizontally oriented micromodels, respectively (Table 3).



at breakthrough (0.03 PV) after 3.2 PV

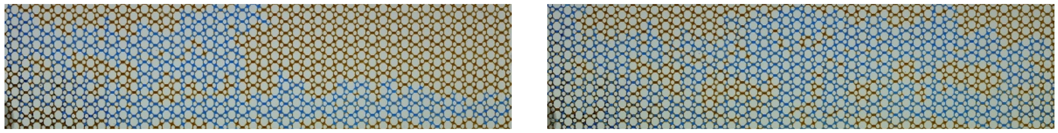
Z
X
Y

**a) With Gravity: Micromodel vertically oriented (Z-X direction), CWI**



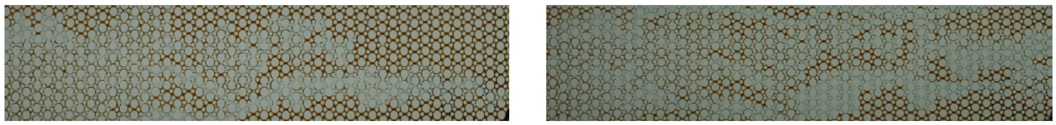
at breakthrough (0.04 PV) after 3.2 PV

**b) Without Gravity: Micromodel horizontally oriented (Y-X direction), CWI**



at breakthrough (0.03 PV) after 3.2 PV

**c) With Gravity: Micromodel vertically oriented (Z-X direction), WF**



at breakthrough (0.03 PV) after 3.2 PV

**d) With Gravity: Micromodel vertically oriented (Z-X direction), Repeat test of (a)**

**Figure 3: Residual oil saturation from secondary CWI and WF**

**Water Flooding vs CWI:** The effect of carbonated water flooding versus water flooding on residual oil saturation is shown in Figure 4, and Table 3. We see that water breakthrough takes a little longer for water flooding (28 min) compared to CWI (24 min - average of the two replicates) possibly due to the mobility of carbonated water. Overall, CWI is more effective at reducing the residual oil saturation at all times after breakthrough (Figure 3c-right and Figure 4) while the residual oil saturation for WF is lower than CWI at breakthrough. The residual oil decreases more with CWI (84.5% to 47.5% - average of the two replicates) vs water flooding (74.3% to 63.8%) post breakthrough, resulting in significantly different residual oil saturations at ~7 PV.

**Effect of Production Rate on CWI:** The effect of production rate in secondary CWI was tested using two production rates, 0.0008 and 0.004 cc/min (Figure 4 and Table 3). The initial displacement was faster for the higher production rate and breakthrough happens earlier, as expected. At the lower production rate, the residual oil saturation profile stabilized at 3.2 PV, but at higher production rate, the oil saturation continued to decrease beyond 3.2 PV. The lower production rate yielded lower residual oil but ultimately the residual oil saturation approached ~50% irrespective of orientation or production rate.

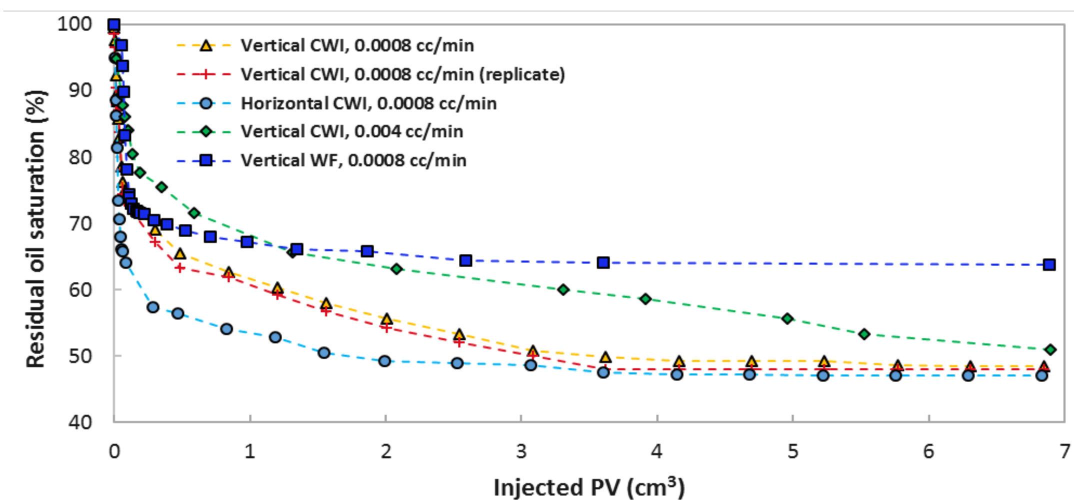


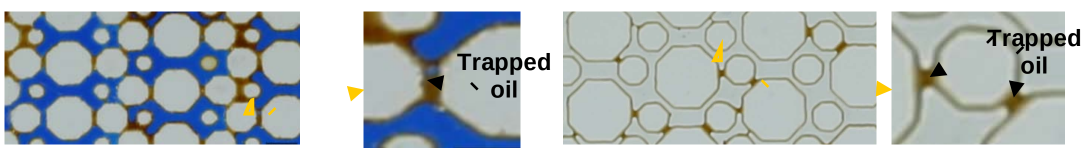

**Figure 4: Residual oil saturation in different scenarios as a function of injected pore volume**

**Table 3: Comparison of different scenarios including WF and SCWI**

| Exp. | Mode | Rate (cc/min) | BT (min) | $S_{or}$ (%) at BT | $S_{or}$ (%) (1 PV) | $S_{or}$ (%) (3.2 PV) | $S_{or}$ (%) (~7 PV) | $N_{ca}$ $\left(\frac{u\mu_w}{\sigma}\right)$ | $N_B$ $\left(\frac{\Delta\rho g K}{\sigma}\right)$ |
|---|---|---|---|---|---|---|---|---|---|
| WF | V | 0.0008 | 28 | 74.3 | 67.3 | 64.1 | 63.8 | 7.25E-8 | 5.82E-5 |
| SCWI | V | 0.0008 | 25 | 85.8 | 61.5 | 50.5 | 47.0 | 7.25E-8 | 6.50E-5 |
| SCWI* | V | 0.0008 | 23 | 83.7 | 58.5 | 48.0 | 48.0 | 7.25E-8 | 6.50E-5 |
| SCWI | H | 0.0008 | 32 | 70.6 | 53.5 | 48.9 | 47.1 | 7.25E-8 | NA |
| SCWI | V | 0.004 | 20 | 80.5 | 68.2 | 61.2 | 53.1 | 3.62E-7 | 6.50E-5 |

WF: water flooding, SCWI: secondary CWI, * repeat, H: horizontal, V: vertical, BT: breakthrough, $S_{or}$: residual oil saturation, $N_{Ca}$: Capillary number, $N_B$: Bond number, $u$: Darcy's velocity =actual velocity *φ *(1-$S_{or}$), (Riazi et al., 2011), g: gravitational force ($m/s^2$), K: permeability ($m^2$), $\Delta\rho$: density difference between displacing and displaced fluids, $\sigma$: Interfacial tension between displacing and displaced fluids.

**Pore scale mechanisms**: The main pore scale mechanisms of oil recovery via CWI compared to water flooding, based on the observed results of this test, are i) the redistribution of trapped oil as a result of oil film flow and ii) reconnection and fluid redistribution within the porous medium, both likely due to $CO_2$ transfer from the water to the oil phase. Figure 5(a) shows trapped oil in the throats at the end of water flooding and Figure 5(b) shows trapped oil in the throats at the end of CWI which is less than that in water flooding.




a b

**Figure 5: Trapped oil in throats a) end of water flooding, b) end of CWI, in presence of gravity (magnified section of micromodel)**

## CONCLUSIONS

Based on the CWI pore scale micromodel experiments, the effect of gravity was verified and earlier breakthrough was observed in the presence of gravity. We observed that the distribution of the carbonated water in the micromodel depends on the oil production rate and orientation. Water flooding was shown to break through after CWI under similar conditions but CWI produces more oil after breakthrough. At lower oil production rates, the carbonated water phase sweeps a larger area and results in less residual oil saturation after breakthrough. Pore scale events such as oil film flow and oil entrapment were observed in both water flooding and CWI. It is believed that $CO_2$ transferred from the water to the oil assisting in trapped oil recovery and film flow for CWI. After the injection of ~7 PV, residual oil approached 50% irrespective of orientation or rate for CWI while it was significantly higher for water flooding at 64% residual oil.

## ACKNOWLEDGEMENTS

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## REFERENCES


1. Rossen, W.R. and C. Shen, “Gravity Segregation in Gas-Injection IOR”, SPE 107262, SPE Europec/EAGE Annual Conference and Exhibition, United Kingdom, 2007.
2. Stone, H. L., “Simultaneous Water and Gas Flood Design with Extraordinary Vertical Gas Sweep”, SPE 91724, SPE International Petroleum Conference, Mexico, 2004.
3. Stone, H. L., “Vertical Conformance in an Alternating Water-Miscible Gas Flood”, SPE 11130, 57th Annual Fall Conference and Exhibition, New Orleans, LA, 1982.
4. Skauge, A., “Comparing Core Analysis Data to Field Observation for Gravity Drainage Gas Injection, SCA 9904, Society of Core Analysts Symposium, 1999, Golden Colorado.
5. James P.M., “Summary of Carbon Dioxide Enhanced Oil Recovery ($CO_2$EOR) Injection Well Technology”, American Petroleum Institute, Annual Report, 2009.
6. Bonnin, E., B. Levallois & G. Joffroy, “Full Field Tertiary Gas Injection, A Case History Offshore Abu Dhabi”, Abu Dhabi, SPE 78362, 10th Abu Dhabi International Exhibition and Conference, 2002.
7. Skauge, A., Kristiansen, J.I. & Søgnesand, S., "Laboratory and Field Measurements of Residual Oil Saturation from Gas Injection at the Oseberg Field" paper number 011, proceeding from EAGE, 9th European Symposium on Improved Oil Recovery, Norway, 1997.
8. Craig, F.F. Jr., “A Laboratory Study of Gravity Segregation in Frontal Drives”, Trans., AIME, Vol. 210, 275-82, 1957.
9. Sandrea, R. & Nielsen R., “Dynamics of Petroleum Reservoirs Under Gas Injection”, Gulf Publishing Company, Book Division, Houston, 1974.
10. Vicente, M., D. Crosta, L. Eliseche, J. Solari and R. Castelo, “Determination of Volumetric Sweep Efficiency in Barrancas Unit, Barrancas Field”, SPE 68806, SPE Western Regional Meeting, California, 2001.
11. Chatzis, I, FAL. Dullien, “Dynamic immiscible displacement mechanisms in pore doublets: theory versus experiment”, Journal of Colloid and Interface Science 91 (1), 199-222, 1983.
12. Kantzas, A., I. Chatzis, FAL. Dullien, “Enhanced oil recovery by inert gas injection, SPE 17379, SPE/DOE Symposium on Enhanced Oil Recovery, Tulsa, 1988.
13. Sohrabi, M., D.H. Tehrani, A. Danesh, G.D. Henderson, “Visualisation of oil recovery by water alternating gas (WAG) injection using high pressure micromodels- oil-wet & mixed-wet systems”, SPE 71494, SPE Journal 9, 290–301, 2004.
14. Riazi, M., Sohrabi, M., and Jamiolahmady, M. “Experimental Study of Pore-Scale Mechanisms of CWI”, Transport in Porous Media, 86:73–86, 2011.
15. Martin, J.W. “Additional oil production through flooding with carbonated water. Producers Monthly, pp 13-15, 1951.
16. Dong, Y., C. Ishizawa, E. Lewis and B. Dindoruk, “Carbonated Water Flood: What be Observed in Sand Pack Experiments”, SCA2011-34, Austin, Texas, 2011.
17. Mosavat, N. and F. Torabi, “Performance of Secondary Carbonated Water Injection in Light Oil Systems”, Ind. Eng. Chem. Res., 53 (3), pp 1262–1273, 2014.
18. Sohrabi, M., Tavakolian, A. Emadi, M. Jami & S. Ireland, “Improved Oil Recovery and Injectivity by Carbonated Water Injection”. SCA2012-05, Aberdeen, Scotland, August 2012.