IMPROVED OIL RECOVERY AND INJECTIVITY BY CARBONATED WATER INJECTION

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ABSTRACT

Despite the recent increased activities around CO2 EOR, lack of an adequate CO2 supply at an affordable price remains a major hurdle in the application of the technique to many oil reservoirs. Moreover, some oil reservoirs, especially those offshore, may not be suitable for any gas-based oil recovery methods including conventional CO2 flood. Oil recovery from these reservoirs may be increased economically by injection of CO2-enriched (carbonated) water. Carbonated water injection (CWI) is a productive and efficient way of using relatively small amount of CO2 as a dissolved phase in the injection water and can be applied instead of conventional water flooding (secondary injection) or after conventional water flooding (tertiary injection).

In this paper, we present the results of a series of coreflood experiments using consolidated cores, crude oil and a synthetic Seawater. The experiments were carried out at 2500 psia and 100 F and include both secondary and tertiary CWI.

The results of the experiments show that significant additional oil recovery was achieved for the crude oil under investigation during tertiary and secondary injection of carbonated water. Compared to conventional water flood, CWI recovered 12% additional oil. The breakthrough of water in CWI took place later than that in plain water injection. In addition to the delay in water breakthrough and a significant improvement in oil recovery, comparison of the differential pressure (DP) across the core in CWI and conventional water flood revealed a lower DP for CWI. This is despite an increase in the viscosity of water when CO2 is dissolved in it and is a clear indication of improvement of the injectivity of CWI compared to water flood. Tertiary injection of carbonated water also resulted in significant additional oil recovery and, for the conditions of our coreflood experiments, 24% additional oil recovery was obtained over and on top of what had already been recovered during the preceding water flood. However, compared to secondary CWI, much larger volume of carbonated water needed to be injected to achieve this high level of additional oil recovery in tertiary mode.

The results also show that, in addition to oil recovery, significant amount of CO2 can be "stored" in the rock during CWI. Since in CWI, CO2 does not exist as a free phase, it

exhibits no tendency for buoyancy driven CO2 leakage, which is a major concern in conventional CO2 injection for the purpose of sequestering CO2 in oil reservoirs.

INTRODUCTION

Oil has powered the world for more than a century now and currently 86% of the world primary energy use is supplied by oil and gas along with coal [1]. Significant effort is being put into developing alternative energy resources and improving energy efficiency. However, the contribution of these energy resources to the world's energy is currently very small and it will take decades before large scale use of these alternative energies materialise. Demand for oil is expected to grow sharply over the long term and between now and 2030, global energy consumption is projected to increase between 40 and 45 percent, with oil, gas and coal, continuing to meet the largest part of that demand. However, the world oil reserves are diminishing and exploration for new discoveries are becoming increasingly more difficult and costly. We therefore need to make better use of the existing oil reservoirs by increasing recovery factor.

Many reservoirs are under water flooding. However, the global waterflood recovery factor is only around 33% and hence significant quantities of oil still remain in place after waterflooding. Oil recovery can be further increased by improving waterflood efficiency (secondary recovery) and/or by applying EOR methods after waterflooding (tertiary oil recovery). Displacement of oil remaining in the reservoir after waterflooding (tertiary oil recovery) is more difficult than oil displacement and recovery by waterflooding. Various techniques are being considered for improving oil recovery by increasing waterflood efficiency. Some of these techniques are chemical based which are, generally speaking, expensive with significant uncertainty around the actual mechanisms of fluid/fluid and rock/fluid interactions taking place during injection. An alternative technique is carbonated (CO2-enriched) water injection. Carbonated water injection (CWI) is a CO2-augmented waterflood (a water-based injectant) process in which relatively small quantities of CO2 is used efficiently without the need for very large supplies/sources of CO2. CWI can be applied as a standalone water injection strategy or can be adapted in conjunction with other oil recovery methods e.g., low salinity (carbonated) water, (carbonated) water and surfactant/polymer injection, carbonated water WAG injection. CWI can be carried out as a secondary (CWI instead of conventional waterflooding) or tertiary (CWI after conventional waterflooding) recovery method.

In CWI, CO2 is used efficiently without a need for very large supply of CO2. This is especially important when CO2 is expensive or its availability is limited (e.g., offshore environment). In these scenarios, in the absence of other cost effective CO2 sources, the amount of CO2 needed for carbonation of flood water may be provided from nearby low-cost CO2 sources e.g., from oil (separated from associated gas) or gas (separated from produced gas).

At Heriot-Watt University we have been investigating the processes involved in oil recovery by CWI at pore and core scale [2-9] since 2006 in a joint industry project (JIP) supported by a consortium of companies. Using high-pressure micromodel technology, we have directly visualized and reported [2, 3, 6, 7, 9] the interactions taking place between the injected carbonated water and the resident fluids (oil and connate water). The level of additional oil recovery and CO2 retention in the rock obtained by CWI have also been studied in our research group by performing core flood experiments [5, 8].

Here we present the results of three new coreflood tests. The results show that carbonation of injection brine can significantly increase oil recovery both in secondary and tertiary (post waterflood) injection modes. The incremental oil recovery due to CWI was produced much quicker during secondary injection of carbonated water compared to tertiary injection.

EXPERIMENT MATERIALS

Rock and Fluids

The core flood experiments reported here have been performed using three separate but similar (companion) Sandstone core samples. The cores were taken from the same block of Clashach rock. Table 1 shows the properties of the cores used in this study. The porosity of the cores was measured using helium and the permeabilities were measured by flowing brine through the cores at test conditions.

The brine used in the experiments was synthetic Seawater. Table 2 shows the composition of the brine and Table 3 shows the viscosity of the brine and carbonated brine at the test conditions of 2500 psia and 100 F and. Carbonated water was prepared by mixing brine with CO2 in a rocking cell under the pressure and temperature of the experiments. While shaking the rocking cell, its pressure was monitored until a stable and steady pressure was achieved which was indicative of the brine being fully saturated with CO2. CW was then separated and stored in a cell in the oven under the tests conditions. The crude oil used in the experiments has an API gravity of 28.55 and a viscosity of 8.54 cp (Stock Tank Oil). The oil had been taken from a reservoir in South America.

Table 1: Core dimensions and properties

Test	**Core**	**Length (cm)**	**Diameter (cm)**	**Porosity (%)**	**Perm. (md)**	**Swi (%)**
CFC1	CC1	32.0	5.0	24.52	1123	35.3
CFC2	CC2	32.0	5.1	23.74	1390	35.4
CFC4	CC3	32.0	5.0	22.62	1369	21.6

Table 2: Composition of the brine

Ion	Concentration (ppm)	Ion	Concentration (ppm)
Na	11700	Ca	1170
Cl	18200	K	123
SO_4	3180	Mg	326
Sr	31	Br	34
Li	22	**TDS**	**35,380 ppm**

Table 3: Viscosity of the plain and carbonated brine at test pressure and temperature.

Fluid	Viscosity (cp)
Brine	0.80
Carbonated Brine	0.88

RESULTS

Water Flood Followed By Tertiary CWI

In this test, a tertiary CWI core flood experiment was performed in order to investigate the potential of CWI for enhancing oil recovery from waterflooded reservoirs. The test pressure and temperature were 2500 psi and 100 ^oF, respectively and the rate of fluid injection in the initial waterflood and the subsequent CWI was the same and equal to 5 cm^3/hr. The test started with the core fully saturated with brine. Then the crude oil was injected through the core, the injection of crude oil continued until the water saturation in the core reduced to 35.3% (i.e., Swi=35.3%). The core was then flooded with brine which resulted in 43% of the oil initially in place (OIIP) to be recovered by this water injection (WI), as shown in Figure 1. After the injection of around 1.5 core pore volume (PV) of water, oil recovery stopped almost completely. After this period of WI, CWI began at the same rate as the WI. Carbonated water was injected for an extended period of time and ultimately a substantial amount of additional oil (24% OIIP) was recovered. Figure 2 shows the amount of oil recovery in this test during both WI and CWI periods. The Figure shows that injecting CW, after plain water, remobilized part of the oil remaining in the rock after “conventional water flooding” and gradually increased the amount of recovered oil. As the injection of carbonated water (CW) continued, production of the oil continued too and after injection of a relatively large volume of CW, oil was still being produced as can be seen from the slope of the oil recovery curve in Figure 2.

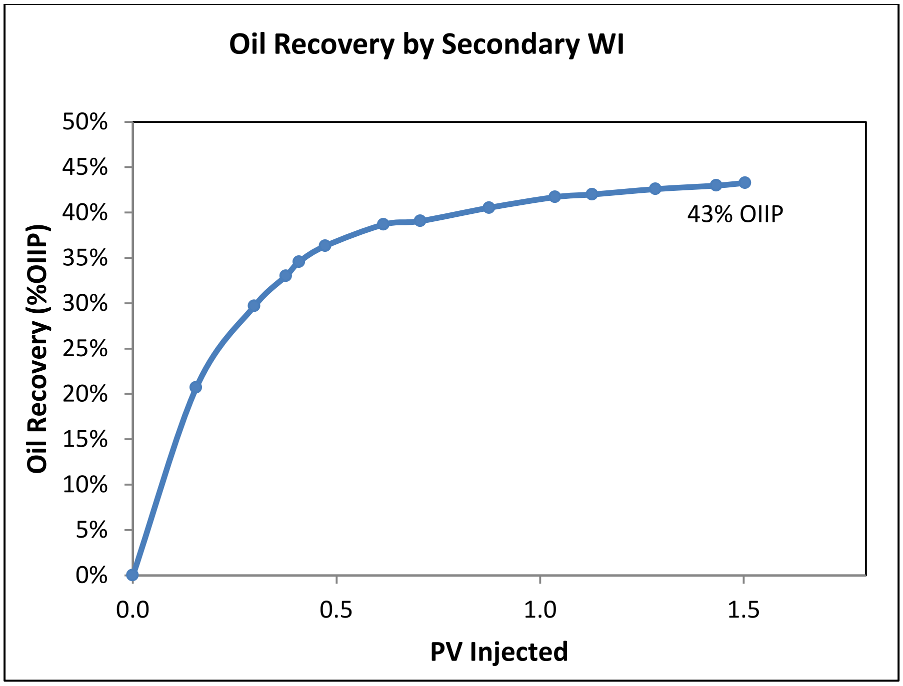

Figure 1 – Oil recovery profile during sencondary WI.

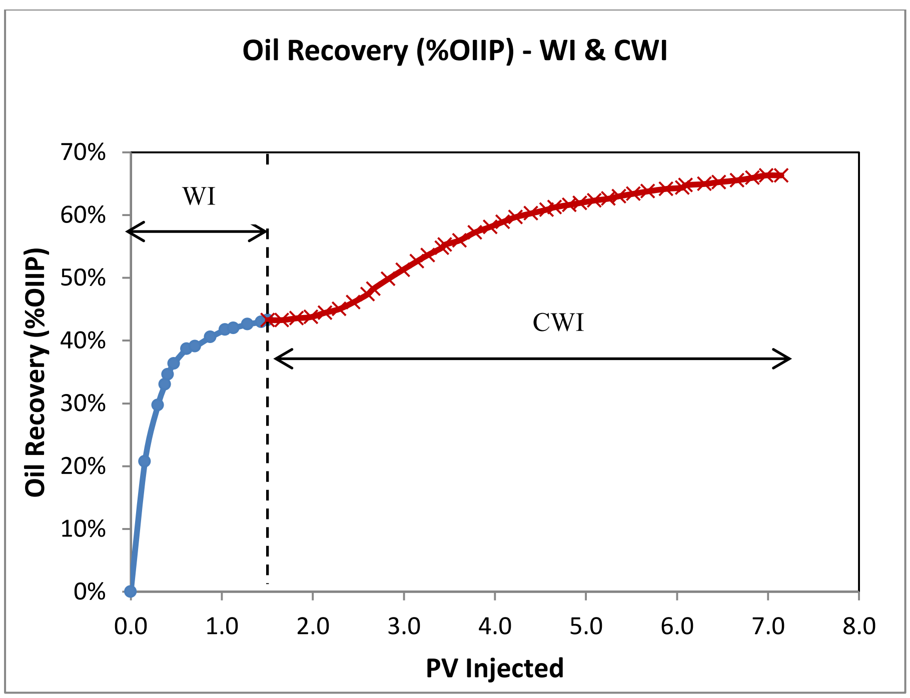

Figure 2 - Oil recovery profile during sencondary WI and the subsequent tertiary CWI.

Secondary CWI

A new Clashach core was used in this test instead of reusing the core that had been used in the previous test. The new core was taken from the same block of Clashach rock that the previous one had been taken from. The reason for using a new core was to ensure that the results of the new test are not affected by possible changes that might have happened to the core due to the injection of CW in the previous test.

In the previous test, CW was injected in tertiary mode after a conventional water injection (WI). The current test was carried out with the main objective of quantifying the level of oil recovery by secondary CWI and to compare this with that obtained by (plain) WI. The same crude oil was used and the test was performed under the same conditions of pressure and temperature and injection flow rates as those in the previous test. The core was first saturated with brine and then the crude oil was injected through the core to establish the initial oil and water saturations (Swi=35.4%). The core was then flooded with CW instead of plain water.
Before injecting CW into the core, the CO_2 content of the CW was measured by flowing CW through the bypass line for some time and collecting and measuring the volume of the CO_2 released from the CW solution using a gasometer. The measured amount of CO_2 dissolved in the brine was 26.47 scm^3/cm^3 (5.93 vol%). CW was then injected through the core at 5 cm^3/hr, which was the same injection rate that had been used in the WI period of the previous test. Injection of CW continued until 2.6 PV of CW had been injected. Figure 3 shows the profile of oil recovery during this secondary CWI period. As can be seen, more than 55% of the OIIP was recovered by CWI, which was much more than the oil recovery achieved by conventional water flooding in the previous test. Figure 4 compares the amount of oil recovery obtained by water injection (WI) with what was obtained by secondary CWI. As can be seen, for the conditions of our experiments, injecting CW instead of plain water, recovered 12.5% additional oil after 2.5 PV of injection. More importantly, the injection of CWI instead of water significantly delayed the breakthrough (BT) of water and increased the amount of oil recovery at the BT. Figure 5 shows a blown up version of the data presented in Figure 4 which highlights the differences between CWI and WI around the water BT which clearly shows a much later BT and much higher oil recovery at BT for the case of CWI. Figure 6 shows the differential pressure (DP) across the core during secondary CWI and during secondary WI which shows a lower DP for CWI compared to plain water injection. As can be seen, despite a higher viscosity of CW compared to plain water, lower DP was required for injecting CW which means higher injectivity and a more efficient displacement process. Comparisons of oil recovery and DP for CWI and WI clearly demonstrate some of the advantages of CWI as a substitute for WI.

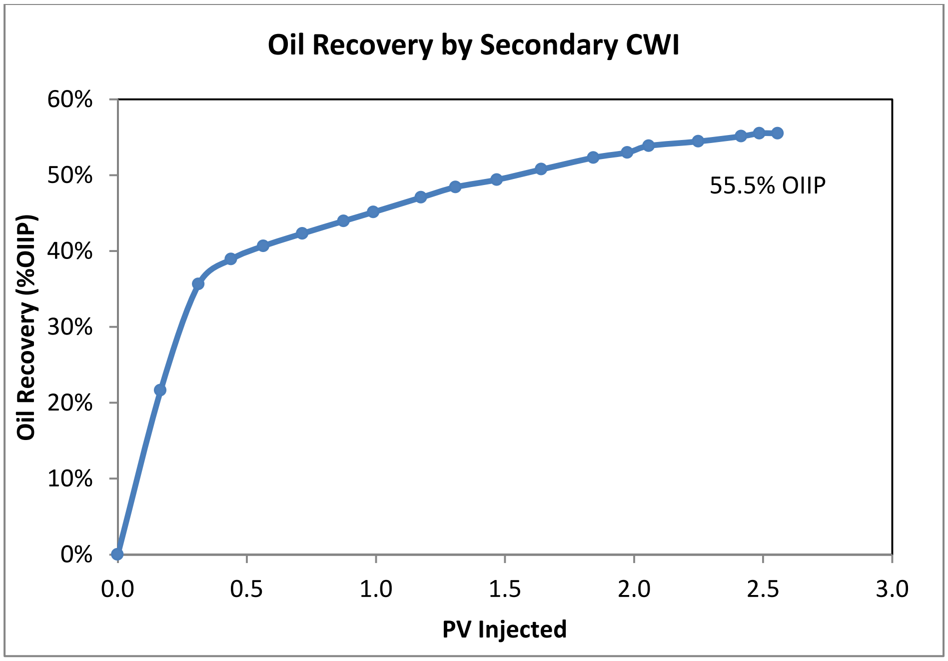

Figure 3 – Oil recovery during secondary CWI period.

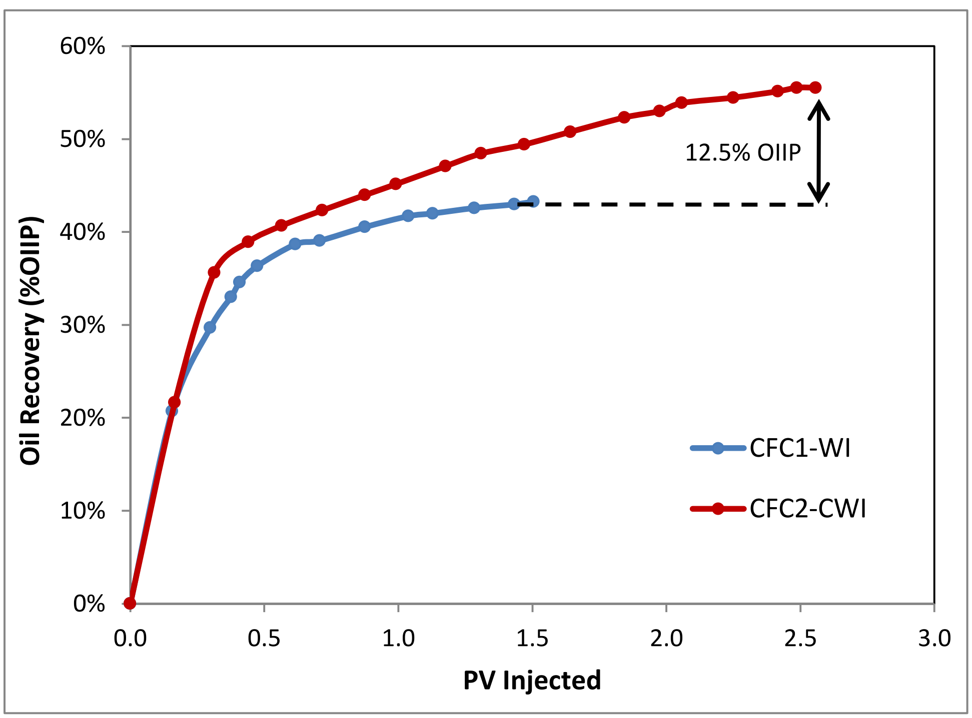

Figure 4 – Comparison of oil recovery by secondary WI (blue curve) and its corresponding secondary CWI (red curve).

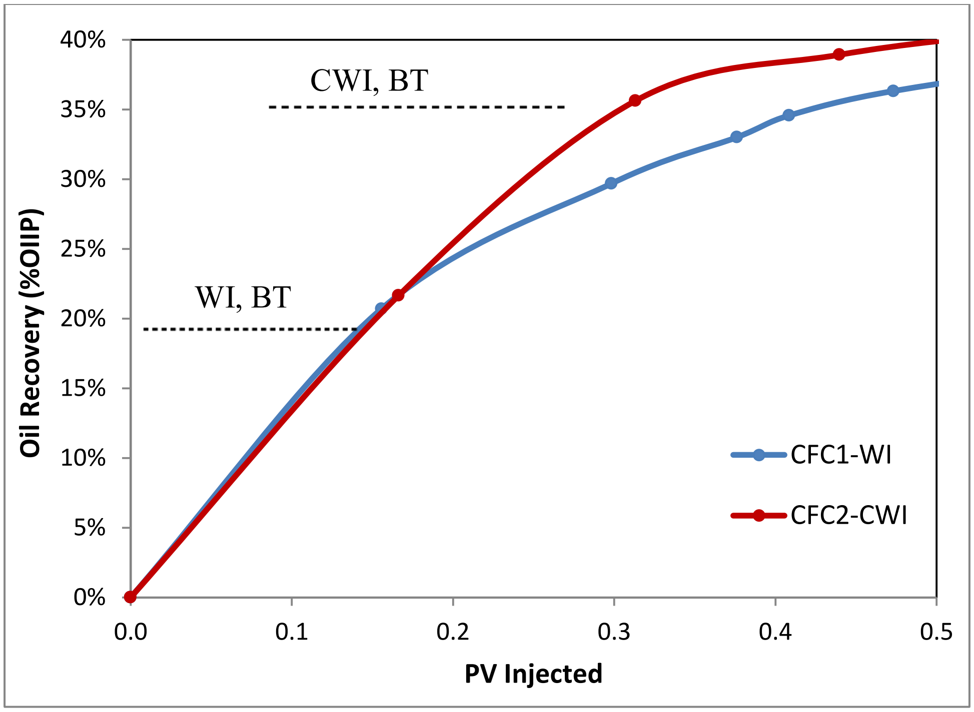

Figure 5 – Comparison of oil recovery by secondary WI (blue curve) and secondary CWI (red curve) around water breakthrough time.

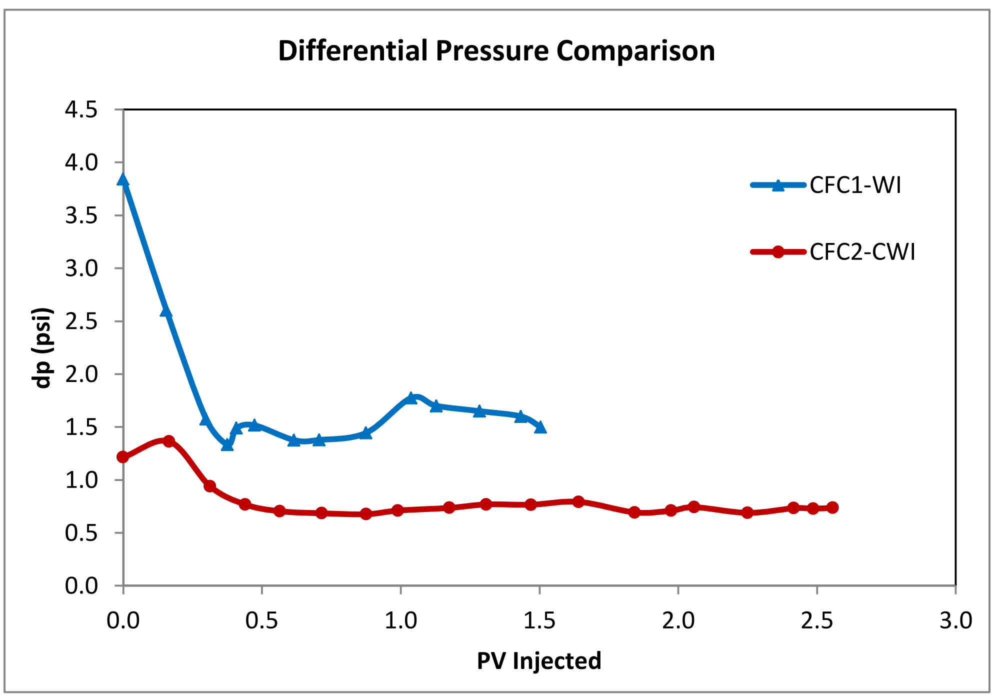

Figure 6 – Comparison of oil recovery by secondary WI (Test CFC1) and its corresponding secondary CWI (Test CFC2).

Water Flood Followed by Tertiary CWI (repeat test)

The additional oil recovered by CWI in both the tertiary and the secondary Tests was substantial and showed huge potential for CWI. However, both tests began with relatively large initial water saturation (Swi) of 35%. To, first, verify that the observed significant additional oil recovery was repeatable and, second, to start with a more realistic and lower Swi, a new Test was carried out. The test was performed at exactly the same pressure and temperature (2500 psi and 100^{o}F) as the previous coreflood tests using the same crude oil. Here again, to avoid any doubts over reusing cores, a new core was used in this test. The test began by establishing a lower Swi of 21% (compared to 35% previously).

The core was then flooded with the brine to physically simulate secondary WI. Water flooding continued until an oil recovery plateau was reached at 41% of OIIP. Figure 7 shows the amount of oil recovery by WI in this test after 1.5 PV of water injection. Tertiary CWI started after this WI. Before injecting CW in the core, the CO2 content of the CWI was measured by flowing CW through the by-pass line. This confirmed a CO2 content value of 28.05 scc/cc which was consistent with the values obtained in the previous tests.

Figure 8 shows the amount of oil recovery by WI and by the subsequent tertiary CWI in the repeat test. As can be seen, as was the case in the original test, here again tertiary CWI resulted in significant additional oil recovery from the waterflooded core. Figure 9, compares the profile of oil recovery obtained in the original test and that obtained in the repeat test. The Figure shows that the amount of oil recovery (based on OIIP%) is very similar in both tests.

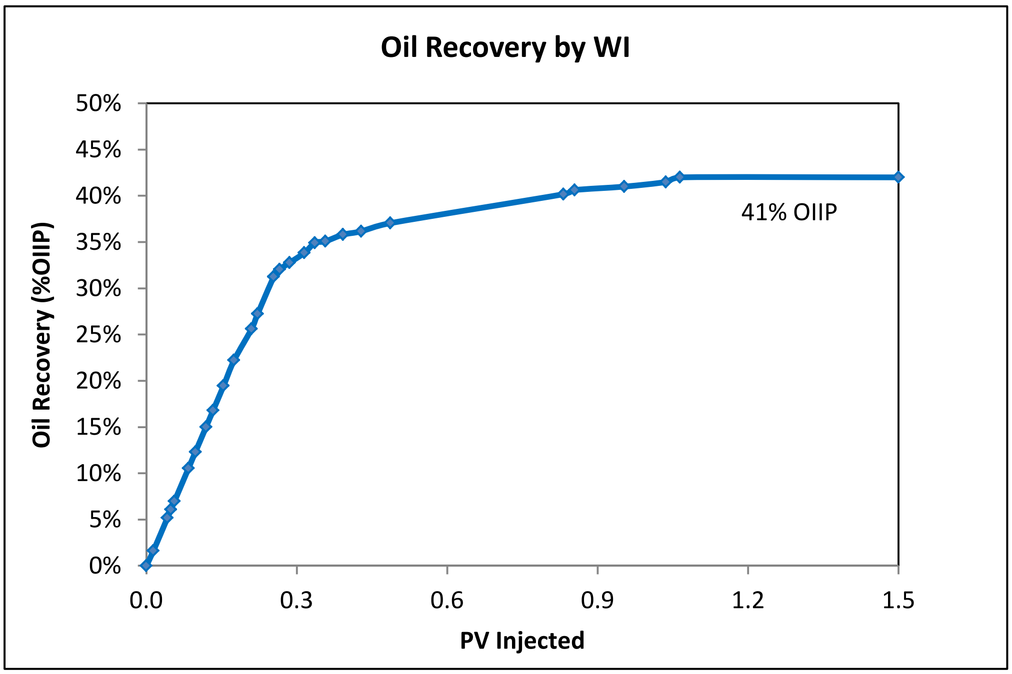

Figure 7 – Oil recovery by secondary WI (repeat Test).

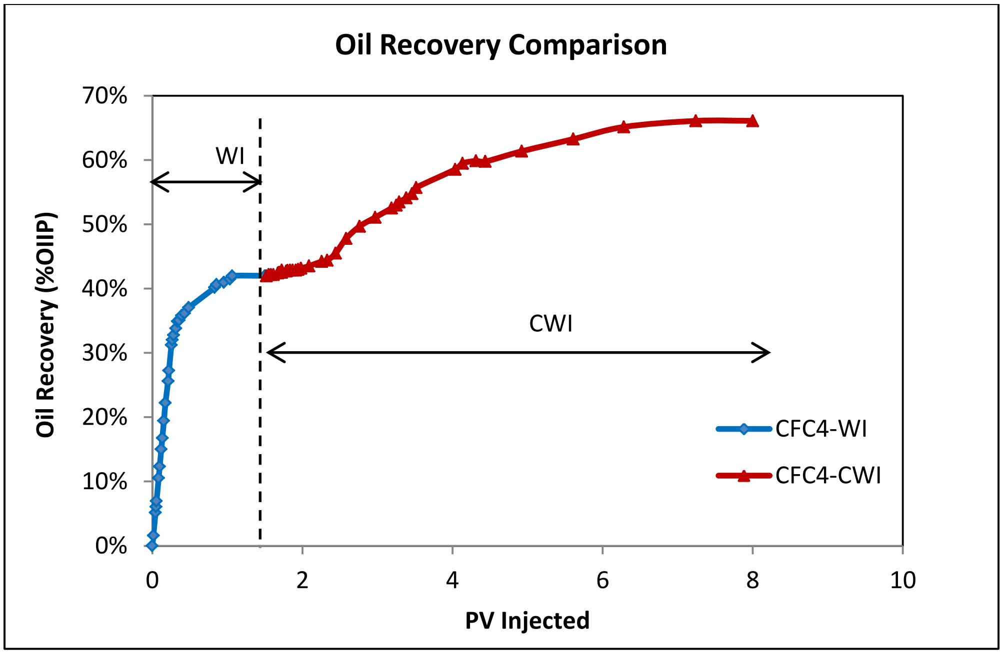

Figure 8 – Oil recovery by secondary WI (blue) followed by CWI (red) obtained in repeat Test.

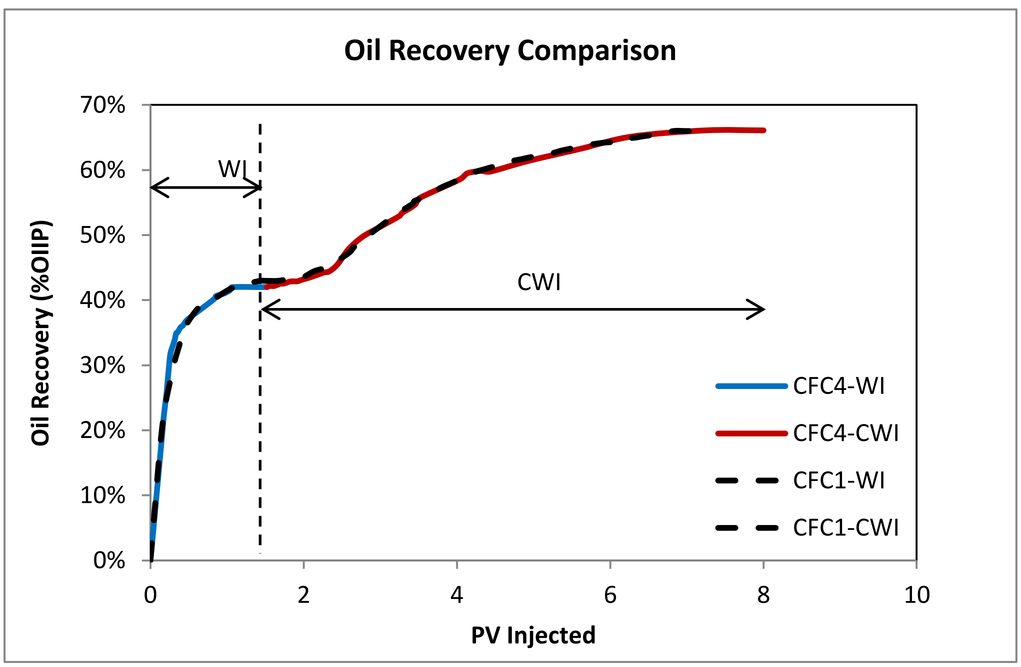

Figure 9 – Comparison of oil recovery by secondary WI and tertiary CWI in two different tests.

CONCLUSIONS

- Both secondary and tertiary CWI have shown significant potential for improving oil recovery. The ultimate oil recovery was higher in tertiary injection but it was more gradual and happened over a much longer period of time.
- In secondary CWI, the water breakthrough was delayed and much more oil was recovered at breakthrough. This demonstrates the great potential of CWI as a substitute for conventional water flood by addition of CO2 to the flood water.
- Comparison of differential pressure (DP) in different tests revealed that despite slight increase in CW viscosity compared to water, lower DP is needed for injecting CWI which implies a better injectivity compared to water injection.

ACKNOWLEDGMENT

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