# Carbonated Water Injection for Heavy Oil Recovery

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**Abstract.** Coreflooding studies were performed at reservoir conditions using a 560-cP heavy crude oil and carbonate core samples. The $CO_2$-enriched injection water was applied after waterflooding for evaluating its potential for improving heavy oil recovery. Results showed that the carbonated water injection achieved an incremental oil recovery of 15.5% of original oil in core (OOIC). This evident incremental production suggests that $CO_2$ effectively diffuses into oil from water, which helps reduce oil viscosity and improve oil mobility. A few tiny dissolved holes were observed at the inlet end face of the core sample after the carbonated water injection. The CT image analysis showed that the rock dissolution was shallow, indicating that the carbonated water injection may not cause evident impact on the carbonate reservoir. For comparison, a hot water flooding test was conducted at 40°C above the reservoir temperature, which achieved an additional oil recovery of 21.0% OOIC. This indicates that the non-thermal technique of carbonated water flooding can achieve a comparable oil recovery enhancement as the hot water flooding for the studied heavy oil reservoir. The results from this work demonstrate the promising potential of the carbonated water flooding for improving the waterflooding performance for heavy oil carbonates.

## 1 Introduction

Reducing water/oil mobility ratio by enhancing oil mobility and/or lowering water mobility is among the most efficient solutions to improve heavy oil recovery. Thermal methods can effectively lower the heavy oil viscosity, leading to significant increase in oil mobility. Therefore, the steam based techniques, such as steam flooding, steam assisted gravity drainage (SAGD) and cyclic steam stimulation (CSS), are the most commonly used methods for heavy oil production. However, many reservoir conditions restrict the application of steam injection, such as thin pay thickness or deep reservoir. Hot water flooding is an alternative thermal option, although it might be less effective than steam injection in terms of heat delivery [1]. Polymer flooding has been recognized as a viable and efficient non-thermal technique to increase heavy oil recovery by reducing water mobility, and successfully applied in many heavy oil reservoirs worldwide [2-5]. Delivering $CO_2$ to heavy oil reservoir is another potential non-thermal solution, which can help remarkably improve oil mobility.

$CO_2$ flooding for enhanced oil recovery has been actively studied and successfully implemented in many fields. The effective oil mobilization by $CO_2$ flood is mainly attributed to the oil viscosity reduction, oil swelling, and/or miscibility [6]. However, some field conditions may restrict its practical application, for instance, the offshore reservoirs, or lack of adequate $CO_2$ supply. Carbonated water flood, injecting $CO_2$-enriched injection water as the displacement fluid instead of the conventional water, is an alternative method to utilize $CO_2$ for improving oil recovery. Except for lack of miscibility, carbonated water injection (CWI) retains most of other benefits of $CO_2$ food. The carbonated water can interact with both reservoir oil and rock, leading to beneficial changes to their properties for oil mobilization. Compared to direct $CO_2$ injection, the CWI can avoid the gravity segregation, which helps to achieve higher sweep efficiency. Compared to conventional waterflooding, the carbonated water injection helps to achieve more favorable mobility ratio. The carbonated water injection reduces oil viscosity due to the diffusion of $CO_2$ from water phase to oil phase. The dissolution of $CO_2$ in oil also causes oil swelling, which leads to higher relative permeability to oil. The oil swelling increases oil saturation, and improves oil phase continuity by reconnecting the isolated oil drops to larger oil ganglia.

Successful field trials of CWI were reported during 1950s to 1960s [7-9]. More than 40% additional oil recovery above the conventional waterflooding was achieved, and evident injectivity improvement was observed. Laboratory studies on CWI were active from 1950s to 1980s [10-13]. In recent years there is a growing interest in reducing carbon foot print, while the energy demand keeps increasing. The researches in CWI are gaining attentions again because it provides a safe and effective $CO_2$ storage solution as well as improving oil recovery [14-16]. The potential of oil recovery improvement by CWI was mainly evaluated by coreflooding studies. Despite the reported incremental oil recovery above the waterflooding had a wide range from 5% to 70% [14], in general, results showed that the CWI can substantially improve oil recovery compared to the conventional waterflooding. It was also revealed that applying CWI in secondary mode was more efficient than in tertiary mode [14-15]. An imbibition study also showed that compared to the unaltered water, the carbonated water accelerated production rate and significantly improved oil recovery [17]. Studies on bulk phase fluid properties, such as solubility, viscosity and volume expansion are commonly conducted to demonstrate the beneficial effects of $CO_2$ injection. High-pressure

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micromodel experiments have also been used to help understand the mechanisms of oil recovery improvement by CWI [15, 16, 18]. The oil viscosity reduction, oil swelling, oil reconnection and redistribution were visually observed during the CWI processes. In addition to altering oil properties, the CWI may also induce interactions between the carbonated water and reservoir rock. An experimental study by contact angle measurements [19] showed that the carbonated water caused varied degrees of wettability alteration depending on the rock properties and test conditions. Laboratory studies on the rock dissolution by carbonated water were also reported for both sandstones and carbonates [20-21].

Most of the studies on $CO_2$ flooding and CWI are for conventional oil. An experimental by Millerand Jones [22] showed that the dissolution of $CO_2$ in heavy oil significantly reduced the oil viscosity, and the viscosity reduction effect tends to be more significant for heavier oil. For a heavy oil with API gravity of 10, the dissolution of $CO_2$ reduced the oil viscosity by a factor of 90 at 2,000 psi and 60°C. Although the swelling effect for viscous oil might be less evident than for light oil [18], the substantial viscosity reduction will help significantly improve oil mobility. With very few studies for heavy oil, and especially for carbonates, in this work we present a laboratory study to evaluate the potential of the carbonated water flooding for carbonate heavy oil reservoirs. A hot water flooding test was also conducted for comparison.

# 2 Experimental Materials

### 2.1 Brines

A synthetic connate water, with a total dissolved solids (TDS) of 136,954 mg/L, was prepared for saturating core plug samples. The waterflooding injection water for coreflooding tests was a synthetic brine with 11,582 mg/L TDS. This brine was also used for preparing carbonated water and for hot water flooding. The detailed brine compositions are presented in Table 1. Both brines were filtered through a 0.45 micron Millipore filter and deaerated for test use.

**Table 1.** Synthetic brine compositions.

| | **Synthetic Connate Water** | **Synthetic Injection Water** |
|---|---|---|
| $Na^+$, mg/L | 41,355 | 3,410 |
| $Ca^{2+}$, mg/L | 8,480 | 684 |
| $Mg^{2+}$, mg/L | 1,453 | 113 |
| $K^+$, mg/L | 1,184 | 261 |
| $Cl^-$, mg/L | 82,982 | 5,756 |
| $SO_4^{2-}$, mg/L | 1,500 | 1,130 |
| $HCO_3^-$, mg/L | / | 228 |
| Total Dissolved Solids, mg/L | 136,954 | 11,582 |

### 2.2 Oil

A dead crude oil from a carbonate reservoir was used for the coreflooding tests. This heavy crude oil has very limited flow ability at room temperature, with oil viscosity of 58,600 cp at 25°C. At test temperature of 77°C, the oil viscosity was 565 cp.

### 2.3 Core samples

Four core plug samples from a carbonate reservoir were used in this study. The composite core sample, composed of two core plugs, was used for each coreflooding test for improving the material balance calculations. The ambient porosity and air permeability of these plugs ranged from 31.1% to 33.4% and 1,396 md to 1,454 md, respectively. Detailed properties of each core plug are presented in Table 2. The carbonated water flooding test was performed on the composite sample built by the first two plugs, while the other two plugs were used for the hot water flooding test.

**Table 2.** Properties of Core Plug Samples.

| Sample | Length cm | Diameter cm | Ambient Porosity % | Ambient Air Permeability md |
|---|---|---|---|---|
| 1 | 5.958 | 3.814 | 32.6 | 1494 |
| 2 | 5.369 | 3.732 | 33.4 | 1454 |
| 3 | 6.010 | 3.778 | 32.4 | 1408 |
| 4 | 5.896 | 3.784 | 31.1 | 1396 |

# 3 Experimental Methods

### 3.1 Coreflooding Experiment

Coreflooding experiments were performed to evaluate the potential of oil recovery improvement by the studied EOR strategies. Oil displacement experiments were conducted at a temperature of 77°C, with a backpressure of 2,600 psi and a confining pressure of 4,240 psi. Injection fluids, oil, brine and carbonated water, were loaded into the piston accumulators and injected into the core sample horizontally by a computer controlled Quizix pump. A constant injection rate of 0.25 ml/min was used for all the oil displacement processes. The pressure drop across the core sample was measured by digital differential pressure transducers. Both the carbonated water and the hot water floodings were performed in tertiary recovery mode to demonstrate the oil recovery improvement potential beyond the conventional waterflooding.

### 3.2 Core Preparation

Before saturating the core samples, computerized tomography (CT) scanning was performed on them to make sure there are no fractures or permeability barriers within the plug samples. Both the visual observation and the CT scanning confirmed that all the selected samples were homogeneous. Following that, the clean and dried core plug samples were first saturated with the synthetic connate water under vacuum, and then applying 2,000 psi pressure to make sure the core samples are fully saturated with the synthetic connate water. The centrifuge method was then used to establish the initial water saturation and saturate with oil. The maximum rotational speed was 4,500 RPM, and the prepared initial water saturation was at around 20% (Table 3). Finally, the oil-saturated core samples were then submerged under crude oil and put to age at reservoir temperature for four weeks.

### 3.3 Carbonated Water Flooding

The carbonated water flooding is an improved oil recovery (IOR) method, which improves the waterflooding performance by injecting $CO_2$-enriched water into the reservoir instead of the conventional injection water. Under the same temperature and pressure conditions, $CO_2$ is more soluble in oil than in water. Therefore, the $CO_2$ dissolved in water will transfer to oil phase after the injection of carbonated water. This will lead to oil viscosity reduction and favorable oil mobility enhancement. The oil volume expansion (swelling effect) is another beneficial effect, which also helps the oil recovery improvement. The oil recovery improvement potential of the carbonated water flooding for recovering heavy oil was evaluated by the coreflooding experiment conducted at reservoir conditions.

In this work, the carbonated water was prepared mainly by following the procedure presented by Dong et al. [14]. The $CO_2$ was mixed with the injection water at ambient temperature and elevated pressure. The $CO_2$ was first injected from a high pressure cylinder into a cylinder filled with the injection water. The sample cylinder was then mounted onto a rocker with a syringe pump connected to support pressure. After rocked for two hours, the $CO_2$-brine mixture was then left overnight to reach equilibrium. A small amount of the mixture sample was withdrawn at a constant pressure and flashed to two phases to measure the gas water ratio (GWR). Based on the correlation by Chang et al. [23], the estimated $CO_2$ solubility in the injection water at reservoir condition was around 20 scc $CO_2$/cc water. To make sure the injection fluid is single phase, the carbonated water was prepared at a lower $CO_2$/water ratio. The measured GWR of the prepared carbonated water before the coreflooding test was 18 scc $CO_2$/cc water.

After loaded into the coreflooding system, the core sample was first flushed with the oil at reservoir conditions to replace the oil in the core, and measure the oil permeability at initial water saturation (Table 3). The oil displacement was started with the conventional waterflooding using the injection water until the oil production was negligible. After that, 5.0 pore volumes (PV) of carbonated water was then injection, and finally followed by a post water flush using the injection water until the oil production was negligible. A constant injection rate of 0.25 ml/min was used in all the displacement processes.

### 3.3 Hot Water Flooding

The major challenge for recovering heavy oil is the low oil mobility, and it is well recognized that thermal methods are among the most effective ways to tackle this problem. Oil viscosity usually decreases exponentially with increasing temperature. In this work, we conducted hot water flooding as a benchmark for the potential in improving heavy oil recovery. Hot water flooding can help significantly reduce oil viscosity, which will lead to remarkable improvement in oil mobility and sweep efficiency. In this study, we performed a water flooding at 120°C, around 40°C above the reservoir temperature, to mimic and evaluate the potential of hot water flooding on oil recovery improvement. The coreflooding procedure was generally the same as that for the carbonated water flooding, with both the hot water and the carbonated water applied in tertiary mode. The conventional waterflooding was first conducted at the temperature of 77°C. Following that, a second water flooding was then perform at 120°C to estimate the recovery potential from hot water flooding. The coreflooding was conducted until the oil production was negligible in each oil displacement stage.

## 4 Results and Discussion

### 4.1 Carbonated Water Flooding

The carbonated water flooding test was conducted on the composite sample composed of core plugs 1 and 2 (Table 2) to evaluate its potential in oil recovery improvement for the studied heavy oil. The carbonated water was injected after a conventional waterflooding, and then followed by a post water flush. Results showed that after around 1.2 PV of water injection, oil recovery reached 16.6% of original oil in core (OOIC) with 95.0% of water cut. After more than 20 PV of water injection, the waterflooding oil recovery reached 33.2% OOIC. Evident oil production improvement was achieved during the carbonated water flooding. After 5.0 PV of carbonated water injection, 13.4% OOIC additional oil was obtained. The final oil recovery reached 48.7% OOIC at the end of the post water flooding, with 15.5% OOIC incremental oil recovery achieved by the tertiary carbonated water flooding. The oil recovery curve and pressure response are plotted in Figure 1. It is noted that the capillary end effect might exist in this test due to the low injection rate. Generally, the carbonated water only has slight effects on water phase viscosity and the oil/water interfacial tension (IFT). At the same injection rate as for waterflooding, the carbonated water injection may not cause evident increase in capillary number. Therefore, the contribution of the end effect reduction to incremental oil might be slight. The evident incremental oil production in this test suggests that $CO_2$ effectively transfers out of the $CO_2$-saturated water and diffuses into the oil. The dissolution of $CO_2$ helps reduce oil viscosity and cause oil swelling, which yields more favorable water-oil mobility ratio. In terms of $CO_2$ utilization, injecting one litre (standard conditions) $CO_2$ produced around 1.3 ml incremental oil. This was consistent with the study results by Dong et al. (2011), which ranged from 0.87 to 1.64 ml incremental oil per litre $CO_2$ injected. The encouraging oil recovery enhancement from this study shows a promising potential of the carbonated water flooding application for the studied heavy oil reservoir.

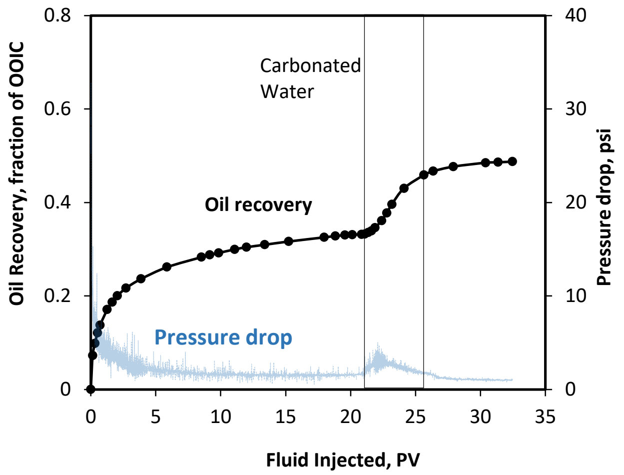


**Fig. 1.** Oil recovery and pressure drop as functions of injected pore volumes. Carbonated water flooding.

After the coreflooding test and unloaded the core sample from the core holder, it was observed that there were a few small holes at the inlet end face of the core sample. This was mainly attributed to the dissolution of rock by the carbonated water. The carbonated water has acidic nature, and it tends to dissolve the carbonate minerals of reservoir rock. The dissolution of the rock may lead to an increase in formation permeability, which can help improve the injectivity. However, it might be complex for sandstone because the dissolution may release cementing particles and cause later precipitation at pore throats. This might lead to the reduction in permeability [20]. For carbonates, the dissolution would generally improve pore connectivity because the carbonate minerals are the major components of the core. This effect was observed in a laboratory study using Middle Eastern carbonated rocks [21]. After large pore volumes of carbonated water injection, it was observed that the pore sizes became larger and some isolated pores were connected.

To help identify the dissolution effect by the carbonated water injection, we performed the CT image analysis on the core plug at the inlet end after the coreflooding test. Figure 2 compares the CT images before and after the coreflooding test. The first row shows four consecutive CT images scanned on the core plug before the coreflooding test. The left side image was the inlet face CT slice, and the thickness of each slice was 0.5 mm. It clearly showed that the core plug was homogeneous before the test. The second row images were the corresponding CT slices obtained after the carbonated water flooding test. The dissolved holes can be clearly observed from the left side two images. Figure 3 presents the CT images from varied view directions after the coreflooding. Generally, this CT image analysis indicated that the rock dissolution was relatively shallow (around 1.0 cm). The carbonated water injection may not cause evident effect on the carbonate reservoir. The similar phenomenon of slight dissolution after carbonated water injection was also observed in a study by Mahzarl et al. [16].

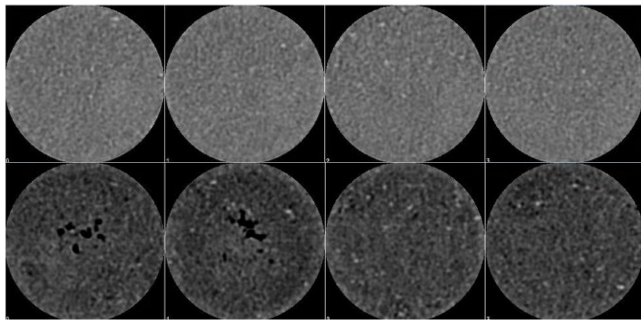

**Fig. 2.** Comparison of CT images before and after carbonated water flooding. The first row were four consecutive CT images scanned on the core plug before coreflooding, and the second row showed the corresponding images obtained after the coreflooding test. The left side image was the inlet face CT slice.

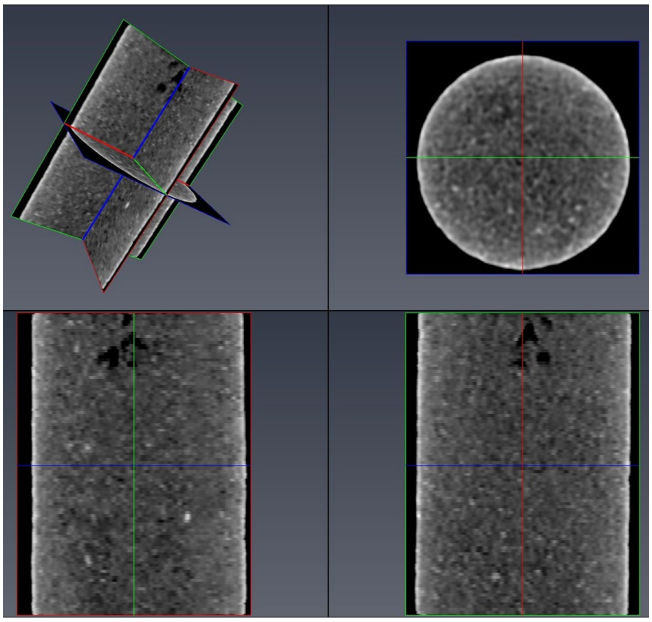

**Fig. 3.** CT images after carbonated water flooding.

### 4.2 Hot Water Flooding

The oil displacement test on the composite core sample 3&4 (Table 2) was performed to demonstrate the potential of hot water flooding in oil recovery enhancement. The conventional waterflooding was first conducted at 77°C. Following that, another waterflooding was then performed at 120°C to mimic the hot waterflooding. Results showed that after around 1.5 PV of water injection the water cut reached around 95.0%, and 20.2% OOIC was recovered. The waterflooding oil recovery after 20 PV of water injection reached 34.9% OOIC. The followed hot water flooding achieved significant additional oil production. The final oil recovery was 55.9% OOIC after 20 PV of hot water injection, with the incremental oil recovery reached 21.0% OOIC. Figure 4 shows the oil recovery and pressure drop as functions of pore volumes injected. Results clearly demonstrate the remarkable potential of the hot water flooding for improving heavy oil recovery. Although it might be less effective than steam flooding in terms of heat delivery, hot water flooding does help evidently reduce oil viscosity. The extrapolated oil viscosity at 120°C based on the Arrhenius-type correlation was around 62 cp, which was only 11% of the original viscosity (565 cp) at 77°C. This dramatic oil viscosity reduction with increasing temperature contributes to the remarkable improvement in oil mobility. We conducted a simple calculation based on the Buckley-Leverett Equation to demonstrate the beneficial effect of oil viscosity reduction on accelerating oil production. All other parameters were kept the same except for the oil viscosity. The Corey correlation was used for relative permeability curves, and the exponents for oil and water phases were 3 and 2, respectively. The residual oil saturation was assumed to be 30%, and the end point water relative permeability was 0.15. Figure 5 compares the calculated oil recoveries for the 565 cp oil and the 62 cp oil. Results clearly showed the favourable effect of oil viscosity reduction on oil recovery improvement and acceleration. It is noted that a same residual oil saturation was used in the calculations. Some research studies [1, 24-25] indicates that oil viscosity reduction may also help reducing residual oil, which would further benefits the oil recovery improvement.

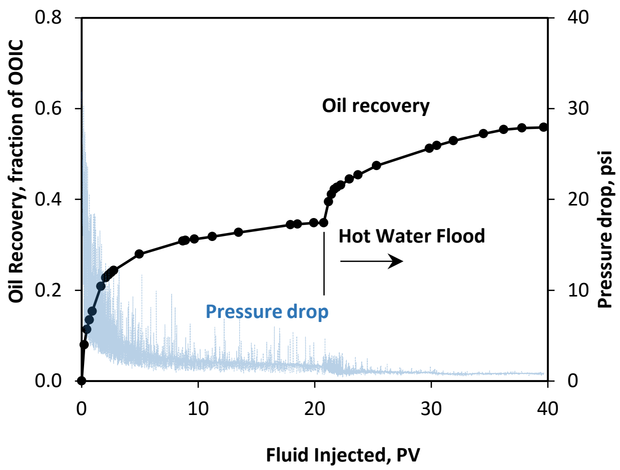


**Fig. 4.** Oil recovery and pressure drop as functions of injected pore volumes. Hot water flooding.

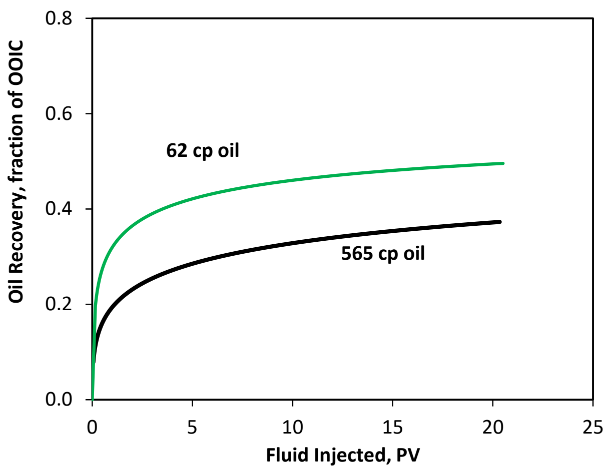


**Fig. 5.** Calculated (Buckley-Leverett Equation) oil recovery curves for 565 cp and 62 cp oils.

### 4.3 Discussion

Figure 6 compares the incremental oil recovery by the carbonated water flooding with that achieved by the hot water flooding during the tertiary production stage. The tertiary oil recovery in this figure was expressed in terms of the remaining oil in core after water flooding (ROIC). The detailed recovery data are summarized in Table 3. As shown in Figure 6, the incremental oil recovery at the end of the carbonated water injection was very close to the result by the hot water flooding after the same amount of water injection. Although hot water floodings at higher temperature will produce more incremental oil [1], the results from this study demonstrate that the carbonated water flooding has a potential to achieve encouraging oil recovery improvement. Delivering $CO_2$ by carbonated water into heavy oil reservoir is an effective solution to help evidently improve oil mobility.

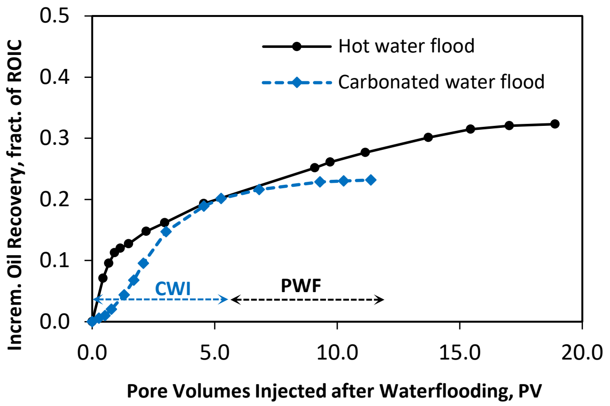


**Fig. 6.** Incremental oil recovery as functions of pore volumes injected after waterflooding. ROIC—remaining oil in core after waterflooding; CWI—carbonated water injection; PWF—post water flush.

**Table 3.** Summary of Oil Recovery Results.

| | Carbonated Water Flooding | Hot Water Flooding |
|---|---|---|
| Core Sample | 1&2 | 3&4 |
| Ambient Porosity, % | 33.0 | 31.7 |
| Air Permeability, md | 1475 | 1402 |
| Initial water saturation, % | 20.6 | 20.7 |
| Oil permeability at Swi, md | 1218 | 1032 |
| Waterflooding oil recovery, %OOIC | 33.2 | 34.9 |
| Incremental recovery at 5.0 PV injection, %ROIC | 19.7 | 19.9 |
| Total incremental oil recovery, %ROIC | 23.2 | 33.1 |
| Final oil recovery, %OOIC | 48.7 | 55.9 |

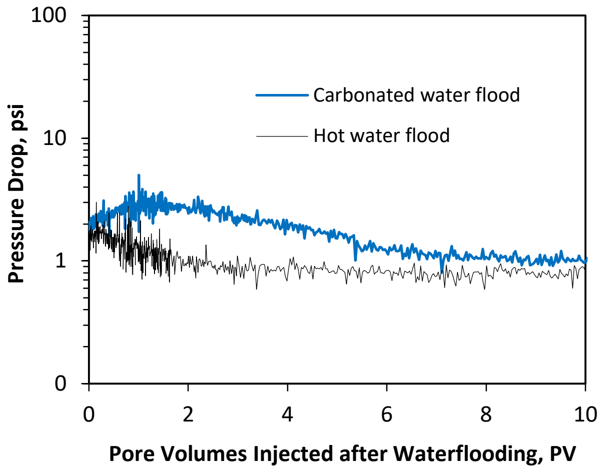


**Fig. 7.** Pressure drop as functions of pore volumes injected after waterflooding.

Figure 7 presents the pressure responses during the tertiary recovery process of both the carbonated water flooding and the hot water flooding. Results showed that when starting the carbonated water injection the pressure increased first, and then gradually decreased after more than 1.0 PV of injection. The pressure increase indicated that the carbonated water contacted with more remaining oil than the preceding plain injection water, which could positively contributed to oil mobilization. The diffusion of $CO_2$ from the carbonated water to oil phase is a relatively slow process. It might take some time or require certain amount of $CO_2$ delivered to achieve evident oil viscosity reduction. Therefore, the oil recovery enhancement by the carbonated water injection is relatively slow at the beginning. The delayed oil response at the earlier stage of the carbonated water injection can also be observed in Figure 6, where the slope of the oil recovery curve was relatively flat. On the contrary, as shown in Figure 7, the injection of hot water immediately led to significant pressure decrease. This indicated that the oil viscosity was effectively reduced at higher temperature, which would significantly enhance the oil mobilization. The steeper oil recovery curve at the earlier stage of hot water injection as shown in Figure 6 evidenced the remarkable response in oil production. In general, the carbonated water flooding can help evidently enhance heavy oil recovery, but the process of production improvement is relatively slower than hot water flooding.

It should be pointed out that the laboratory evaluations intend to study the ultimate potential in oil recovery improvement. The complex reservoir environment and operation processes usually have great impact on the actual results of field applications. For instance, the reservoir temperature is not constant during the hot water flooding. This would induce viscosity gradient and limit the efficiency of the process.

## 5 Conclusions

We evaluated carbonated water flood through a core flooding study for its potential application for a carbonate heavy oil reservoir. Hot water flooding was also conducted for comparison. The following conclusions are drawn from this study:

- The carbonated water flooding applied in tertiary mode achieved 15.5% OOIC of oil recovery improvement for the studied heavy oil. This indicates that the oil viscosity is effectively reduced by the transfer of $CO_2$ from water to oil phase, and injecting carbonated water is more favorable than the conventional waterflooding.

- The hot water flooding performed at 120°C produced additional 21.0% OOIC incremental oil beyond waterflooding. This demonstrates the effectiveness of hot water flooding as well as the higher capacity of thermal techniques in oil mobility enhancement.

- Injecting carbonated water to carbonate core caused rock dissolution. The CT image analysis indicated that the rock dissolution was relatively shallow, and the carbonated water injection may not cause evident impact on the carbonate reservoir.

- The results from this work demonstrate the promising potential of the carbonated water flooding for improving the waterflooding performance for heavy oil carbonates. The incremental oil recoveries for both processes might be slightly overestimated due to the capillary end effect, but the general trend in oil recovery enhancement should be intact. Higher oil recovery enhancement is also expected upon further optimization studies.

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