Experimental Investigation of the EOR Performances of Carbonated Water Injection in Tight Sandstone Oil Reservoirs

Xuefeng Qu¹, Qihong Lei¹, Youan He¹, Zhewei Chen², and Haiyang Yu², *

¹ Research Institute of Exploration and Development, Petro China Changqing Oilfield Company, Xi’an, China.
² State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum, Beijing, China.

*Corresponding author e-mail: haiyangyu.cup@139.com

Abstract. Carbonated water injection (CWI) refers to a method that using carbonated water (CO₂ dissolved in water under high pressure) as injected fluid to displace oil in the reservoir. At present there is no report about CWI study in tight oil reservoirs. Based on the reservoir condition and material of a tight formation in Changqing Oilfield, we investigate the core displacement performances of CWI, water alternating Gas (CO₂), surfactant injection, and active carbonated water (adding surfactant in carbonated water) injection. Experimental results demonstrate that CWI recovery is 7.2% more than water injection, and 2.7% more than WAG injection; ACWI achieves the best performance with 10% more oil recovery than water injection.

1. Introduction

Increasing energy consumption has moved industrial exploration towards developing tight oil reservoirs. However, tight oil reservoirs are very hard to recover hydrocarbon because of its extremely low permeability and complex fractures[1,2]. For example, Changqing Oilfield located in Ordos basin, a typical tight oil reservoir, the oil recovery is generally less than 8% of the original oil in place (OOIP)[3]. Conventional secondary oil recovery methods, like water injection and gas injection did not have a significant enhanced oil recovery (EOR) performance in tight oil reservoirs. Water flooding has the problem of limited enhanced oil recovery due to its low sweep efficiency. Gas injection brings about serious breakthrough because of obvious viscosity difference between gas and oil[4,5]. Other methods like water-alternating-gas (WAG) do not solve this problem effectively[6]. Gas breakthrough becomes the most serious problem during the gas injection process in tight oil reservoirs[7].

Carbonated water injection (CWI) refers to a method that using carbonated water (an amount of CO₂ dissolved in water under certain pressure and temperature) as injected fluid to displace oil in the reservoir. CWI is a combined injection method which integrates the advantage of water flooding and CO₂ injection. The main EOR mechanism of CWI is that CO₂ has a higher solubility in oil phase than in water phase, so CO₂ would gradually transfer to residual oil from injected water, leading oil swelling, viscosity reduction, wettability improvement, etc. [8, 9]. CWI is able to reduce gas breakthrough of CO₂ flooding, and to improve sweep efficiency of water flooding. Besides, many oilfields lack sufficient CO₂ source
in place and the costs of CO₂ gas transfer and storage are expensive. So it is important to improve the efficiency of CO₂ usage, thereby making CWI an alternative option.

In the past few decades, several researchers and companies had conducted lab-scale experiments and field application of CWI[10-18]. In lab-scale experiments, the test results showed that CWI can significantly improve oil recovery than water flooding[10-13]. Mosavat and Torabi’s experiments shows that CWI had an incremental ultimate oil recovery of 19% compared with water flooding [12,13]. Field applications shows great potential of CWI with a distinctly increasing of oil rate, achieved significant EOR performance in conventional reservoirs[14-17]. Taking K&S project for example, the estimated Water flooding potential production was 125 STB/acre-ft. However, after carbonated water flooding, the real production was 161 STB/acre-ft. Carbonated water flooding has the ability to increase 37% more oil than Water flooding[18].

Dong et al.[19] studied the influence of adding active component in carbonated water. The study indicated that active component can reduce the interfacial tension between oil and carbonated water, and more CO₂ would be easier to transfer to oil phase from water phase, which would improve the CWI performance. In addition, carbonated water has the ability to replace and disseminate the surfactant adsorbed in formation[14], so it can improve surfactant flooding performance. Therefore, using active carbonated water (adding surfactant in carbonated water, ACW) may have better EOR performance than conventional CWI.

However, all existing study of CWI and ACWI are conducted for conventional reservoirs. So far there is no report about CWI study in tight oil reservoirs and it is still unknown for the EOR performance of CWI and ACWI.

This paper conducts a serious of core flooding experiments, using material from Changqing tight oil formation, to evaluate the EOR performance of carbonated water injection, active carbonated water injection (ACWI), surfactant injection and water altering CO₂.

2. Experimental setup and procedures

2.1. Core flooding rig

Figure 1 illustrates the core flooding rig. As for injected fluid, brine (formation water), oil, surfactant solution, carbonated water, active carbonated water and CO₂ are stored in pump vessels and then injected into the core sample by a pump as needed. Core flooding experiments was conducted under the reservoir condition, average pressure of the system was 15MPa and temperature was 60℃. The core flooding rig can withstand maximum temperature of 150℃ and maximum pressure of 60MPa, so it is suitable for the core flooding experiment.

![Figure 1. Sketch of core flooding apparatus](image)
2.2. Materials

2.2.1. Core sample. Sandstone core samples with a diameter of 2.5 cm from Chang 7 formation of Ordos Basin are used in the experiments. Before core flooding experiments, cores were cleaned and saturated by formation water and dead oil. The properties of core samples are presented in Table 1.

| Sample | Length, cm | Porosity, % | Permeability, mD | Initial Oil Saturation, % |
|--------|------------|-------------|------------------|--------------------------|
| CQ-1   | 5.90       | 12.50       | 0.10             | 56.80                    |
| CQ-2   | 6.21       | 12.60       | 0.11             | 56.00                    |
| CQ-3   | 5.40       | 12.37       | 0.21             | 54.93                    |
| CQ-4   | 6.40       | 11.37       | 0.17             | 55.44                    |

2.2.2. Oil sample. The oil sample from Chang 7 formation of Ordos Basin is used in the experiments. The dead oil has low density and viscosity of 775 kg/m³ and 4 mPa·s respectively at 60℃ and atmospheric pressure. The components of dead oil are measured by Agilent 7890A Gas Chromatograph and result is presented in Table 2.

| Component | wt% | Component | wt% | Component | wt% |
|-----------|-----|-----------|-----|-----------|-----|
| C3        | 0.06| C13       | 5   | C23       | 3.31|
| C4        | 0.32| C14       | 5.32| C24       | 2.94|
| C5        | 0.93| C15       | 5.35| C25       | 2.89|
| C6        | 3.24| C16       | 4.63| C26       | 2.66|
| C7        | 6.13| C17       | 4.75| C27       | 2.4 |
| C8        | 6.33| C18       | 4.42| C28       | 1.88|
| C9        | 3.95| C19       | 4.7 | C29       | 1.62|
| C10       | 4.17| C20       | 4.13| C30       | 1.05|
| C11       | 4.39| C21       | 3.88| C31+      | 1.59|
| C12       | 4.39| C22       | 3.57| TOTAL     | 100 |

2.2.3. Formation water sample. The brine is prepared according to the composition of formation water. The composition of brine is presented in Table 3. The brine has density and viscosity of 1120 kg/m³ and 0.5 mPa·s respectively at 60℃ and atmospheric pressure.

| Anion (mg/L) | Cation (mg/L) | Salinity (mg/L) |
|--------------|--------------|-----------------|
| K⁺ + Na⁺     | Ca²⁺         | Cl⁻             | SO₄²⁻        | HCO₃⁻       | 53900         |
| 16207        | 2528         | 270             | 29703        | 734          | 337           |

2.2.4. Surfactant. The surfactant “CQ-II” used in the experiments are synthesized by Changping Oil Field Company. Interfacial tension (IFT) of oil and water in different surfactant concentrations are measured by a Spinning Drop Tension Meter. Figure 2 illustrates oil drops and IFT in different concentrations of surfactant solution, test result shows that IFT reaches a minimum level at a surfactant concentration of 0.02 wt%. Based on the IFT test, the surfactant solution of 0.1 wt% would be used in surfactant injection and ACWI experiment, considering the possibility of adsorption or retention effect.
2.3. Experimental procedures

The core flooding experiment parameters are listed in Table 4, and procedures of core flooding experiments are conducted as follows.

1) Water injection stage experiments:
   Synthetic brine is injected into the core. After no oil observed at outlet side, brine would continue to be injected until total volume of injected brine reached 2PV.

2) Surfactant injection/WAG/CWI/ACWI EOR stage experiments:
   For surfactant injection/CWI/ACWI EOR stage experiments, after 2PV brine is injected, 2PV surfactant solution/CW/ACW would be injected.
   For WAG EOR experiment, after 2PV brine is injected, 2 cycles of WAG would be conducted. When volume of CO$_2$ injection reaches the set value, brine would be injected until total volume of injected fluid reached 4PV.

Table 4. Experimental parameter

| Experimental parameter                        | Value  |
|----------------------------------------------|--------|
| Injection Rate, mL/min                       | 0.1    |
| Temperature, °C                              | 60     |
| Outlet Pressure, MPa                         | 8      |
| Injected CO$_2$ Volume/Pore Volume (for WAG/CWI/ACWI), cm$^3$/cm$^3$ | 1.0    |

3. Result and discussion

3.1. Experiments results

Figure 3 and Table 5 illustrate EOR performances of surfactant injection/WAG/CWI/ACWI.
Table 5. Experimental result of the core displacement

| Experiments | 1    | 2    | 3    | 4    |
|-------------|------|------|------|------|
| Core sample | CQ-1 | CQ-2 | CQ-3 | CQ-4 |
| Oil recovery of water injection, % | 31.53 | 29.28 | 28.89 | 29.40 |
| EOR method | Surfactant | WAG | CW | ACW |
| Oil recovery of EOR method, % | 33.58 | 33.81 | 36.11 | 39.41 |
| Incremental oil recovery, % | 2.05 | 4.53 | 7.22 | 10.01 |

After water injection, surfactant injection increases an oil recovery of 2.05%. However, surfactant injection has limited EOR ability, compared to the other EOR methods. WAG is effective at the beginning of EOR stage and has an incremental oil recovery of 4.53% eventually. CWI has a better EOR performance than WAG and has an incremental oil recovery of 7.22%. In addition, ACWI achieves the best EOR performance among 4 EOR methods and has an incremental oil recovery of 10.01%.

3.2. Comparison of CWI and WAG
Compared CWI with WAG in Figure 3(a), WAG has a higher oil rate at the beginning of EOR stage. However, with a limited CO₂ volume, carbonated water injection has a higher incremental oil recovery than WAG at the end. Carbonated water injection can achieve a better EOR performance with more efficiently of CO₂ usage.

3.3. Comparison of ACWI and CWI
Compared ACWI with CWI in Figure 3(a), ACWI improves oil rate while the oil rate of CWI is rather slow at the beginning of EOR stage. ACWI also has more incremental oil recovery of 2.78% than CWI. ACWI achieves a better EOR performance: not only improves the wettability of core sample, but also improves the efficiency of CO₂ transfer from water phase to oil phase, leading a better EOR performance of CWI.

4. Conclusion
The following main conclusions are drawn based on the experiment results presented in this paper:

(1). Carbonated water injection has an incremental oil recovery of 7.22% compared with water injection. Incremental oil recovery of carbonated water injection is more than WAG and surfactant injection.

(2). Active carbonated water injection achieved the best EOR performance with an incremental oil recovery of 10.01% among ACWI, CWI, WAG and surfactant injection. Compared with CWI, ACWI can improve oil rate at the beginning of EOR stage.

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References
[1] C. A. Green, R. D. Barree and J. L. Miskimins, Hydraulic-Fracture-Model Sensitivity Analyses of a Massively Stacked, Lenticular, Tight Gas Reservoir, 2009, SPE Prod & Oper. 24 (01): 66-73.
[2] M. S. Kanfar, S. M. Ghaderi, C. R. Clarkson, et al, A Modeling Study of EOR Potential for CO₂ Huff-n-Puff in Tight Oil Reservoirs - Example from the Bakken Formation, the SPE Unconventional Resources Conference, Calgary, Alberta, Canada, 15-16 February, 2017.
[3] Y. He, S. Cheng, J. Qin, et al, Successful Application of Well Testing and Electrical Resistance Tomography To Determine Production Contribution of Individual Fracture and Water-breakthrough Locations of Multifractured Horizontal Well in Changqing Oil Field, China. SPE
Annual Technical Conference and Exhibition, San Antonio, Texas, 9-11 October, 2017.

[4] K. Zhang, K. Sebakhy, K. Wu, et al. Future Trends for Tight Oil Exploitation. the SPE North Africa Technical Conference and Exhibition, Cairo, Egypt, 14-16 September, 2015.

[5] F. Kamali, F. Hussain, and Y. Cinar. An Experimental and Numerical Analysis of Water-Alternating-Gas and Simultaneous-Water-and-Gas Displacements for Carbon Dioxide Enhanced Oil Recovery and Storage, 2017, SPE J. 22 (02): 521-538.

[6] L. Han, and Y. Gu, Miscible CO₂ Water-Alternating-Gas (CO₂-WAG) Injection in a Tight Oil Formation, the SPE Annual Technical Conference and Exhibition, Houston, Texas, USA, 28-30 September, 2015.

[7] H. Wang, X. Liao, X. Zhao et al. The Study of CO₂ Flooding of Horizontal Well with SRV in Tight Oil Reservoir, the SPE Energy Resources Conference, Port of Spain, Trinidad and Tobago, 9-11 June, 2014.

[8] M. Riazi, M. Sohrabi, M. Jamiolahmady, Experimental study of pore-scale mechanisms of carbonated water injection, 2011, Transp Porous Med. 86, 73–86.

[9] M. Riazi, M. Sohrabi, M. Jamiolahmady et al. Direct observation of CO₂ transport and oil displacement mechanisms in CO₂/water/oil systems, 15th European Symposium on Improved Oil Recovery, Paris, France, 27-29 April, 2009.

[10] M. Hasanvand, M. Ahmadi, S.R. Shadizadeh et al., Geological storage of carbon dioxide by injection of carbonated water in an Iranian oil reservoir: a case study, 2013, J. Pet. Sci. Eng. 111, 170–177.

[11] A.H. Alizadeh, M. Khishvand, M.A.Ioannidis et al., Multi-scale experimental study of carbonated water injection: an effective process for mobilization and recovery of trapped oil, 2014, Fuel 132 (2014): 219–235.

[12] N. Mosavat and F. Torabi, Performance of secondary carbonated water injection in light oil systems, 2014, Ind & Eng. Chem. Res. 53: 1262–1273.

[13] N. Mosavat and F. Torabi, Experimental evaluation of the performance of carbonated water injection (CWI) under various operating conditions in light oil systems, 2014, Fuel. 123 (2014), 274–284.

[14] R. J. Christensen, Carbonated Waterflood Results – Texas and Oklahoma, the 7th Annual Meeting of Rocky Mountain Petroleum Sections of AIME

[15] C. W. Hickok, R. J. Christensen, and H. J. Ramsay Jr.: “Progress Review of the K&S Carbonated Waterflood Project,” Journal of Petroleum Technology, 1960, 20-24

[16] C. W. Hickok and H. J. Ramsay Jr., Case Histories of Carbonated Water Floods in Dewey-Bartlesville Field, Producer Monthly, August 1962

[17] J. O. Scott, and C. E. Forrester, Performance of Domes Unit Carbonated Waterflood – First Stage, Journal of Petroleum Technology, 1965: 1379-1384

[18] Y. Dong, B. Dindoruk, C. Ishizawa, et al. An Experimental Investigation of Carbonated Water Flooding, the SPE Annual Technical Conference and Exhibition held in Denver, Colorado, USA, 30 October–2 November, 2011.

[19] Y. Dong, C. Ishizawa, E. Lewis et al. Carbonated water flood: what we observed in sand pack experiments, International Symposium of the Society of Core Analysts, Austin, TX; September 18–21, 2011.