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EXPERIMENTAL RESEARCH AND FIELD IMPLEMENTATION OF CARBONATED WATER INJECTION TO ENHANCE OIL RECOVERY

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Abstract

Carbon dioxide is a major greenhouse gas that leads to global warming. Injection of CO_2 into oil reservoirs not only improves oil recovery but also stores large quantities of CO_2 in the reservoir. However,the limited supply of carbon dioxide often restricts the implementation of CO_2 flooding projects. Carbonated water injection (CWI) can be a good alternative when carbon dioxide is inadequate. Laboratory tests revealed that CO_2 effectively improved oil recovery by increasing oil volume and reducing oil viscosity. Several field cases in the USA demonstrated that CWI not only improved oil production but also enhanced water injection.

***Keywords**: Carbon dioxide; Oil recovery; Carbonated water; Literature review.*

1. Introduction

After primary recovery and secondary recovery processes, usually more than 50% OOIP (original oil in place) still remains in reservoirs. Various methods have been developed to improve oil recovery. The most widely-adopted enhanced oil recovery (EOR) methods include steam injection, polymer flooding, and carbon dioxide injection.

Carbon dioxide generated by the consumption of fossil fuel is regarded as a major greenhouse gas that contributes to global warming. On the other hand, carbon dioxide can be injected into oil reservoirs to enhance oil production [1]. Moreover, large quantities of carbon dioxide can be stored underground, which reduces carbon dioxide emission to the atmosphere [2].

Large-scale carbon dioxide EOR projects are underway in the USA and Canada. Kinder Morgan Company injects 1.2 Bcf (billion cubic feet) of carbon dioxide per day in Texas and New Mexico oil fields [3], including SACROC unit, Yates field, Katz unit, and Tall Cotton unit in Texas, as shown in Fig. 1. The Weyburn field in Canada aims to store 30 million tons of carbon dioxide over 30 years [4]. Moreover, these projects proved to be financial successes because the additional oil production pays for the cost of carbon dioxide.

However, carbon dioxide EOR projects face several challenges. Projects are often restricted by the supply of carbon dioxide. Most of the carbon dioxide EOR projects are conducted in North America, where carbon dioxide supply is adequate [5]. However, the success in the USA and Canada cannot be easily duplicated in other regions, because of the shortage of carbon dioxide supply elsewhere. Secondly, carbon dioxide is much less viscous than reservoir oil. The injected carbon dioxide thus channels through the high-permeability strata without sweeping oil effectively. As a result, the carbon dioxide EOR projects in USA and Turkey reported early gas breakthrough [6].

When the supply of carbon dioxide is limited, carbonated water injection (CWI) may be a good alternative to carbon dioxide injection. The CWI process is to inject water saturated with carbon dioxide into reservoirs. Carbon dioxide in the carbonated water diffuses into oil and mobilizes the residual oil. Compared with carbon dioxide injection, CWI requires much less supply of carbon dioxide [7].

Besides, carbonated water has a much higher viscosity than pure carbon dioxide gas. As a result, the tendencies of gas channeling and early breakthrough are reduced. Moreover, CWI can be applied to reservoirs with high temperature and high salinity. For such harsh reservoirs, polymer injection has a slim chance to succeed [8-9].

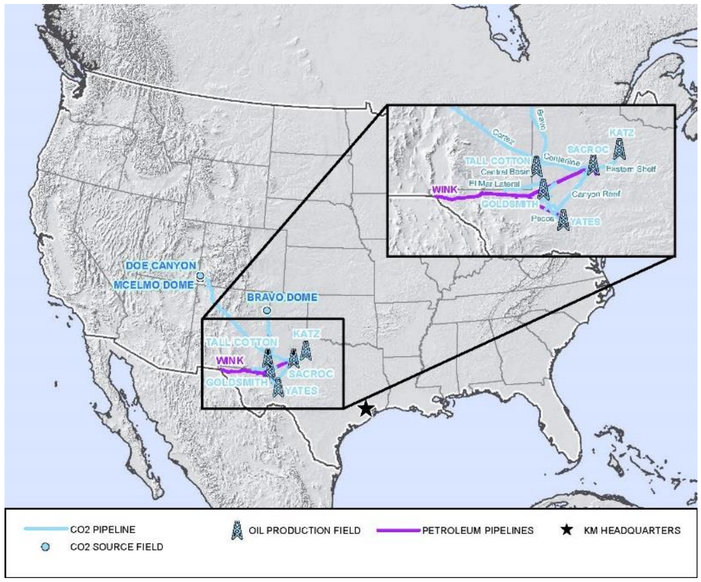

Fig. 1. Carbon dioxide EOR projects in Texas

2. Influences of carbon dioxide on oil and rock properties

After carbonated water is injected into the reservoir, carbon dioxide diffuses into oil because of the higher solubility of carbon dioxide in oil than in water. Experiments were conducted to study the solubility of carbon dioxide in hexadecane and heavy oil [10]. The properties of oil samples are presented in Table 1. The solubility test results are presented in Fig. 2. It can be concluded a significant amount of carbon dioxide can dissolve in oil, especially at high pressure. Besides, dissolution of carbon dioxide led to a reduction in oil viscosity, as shown in Fig. 3. Heavy oil viscosity reduced from 172 to 120 cP after 8 hours of contact with carbon dioxide at 50°C.

Table 1. Properties of oil samples

Oil sample	Specific gravity	API gravity	Viscosity at 50°C (cP)
Hexadecane	0.77	55.6	2.8
Heavy Oil	0.97	13	172

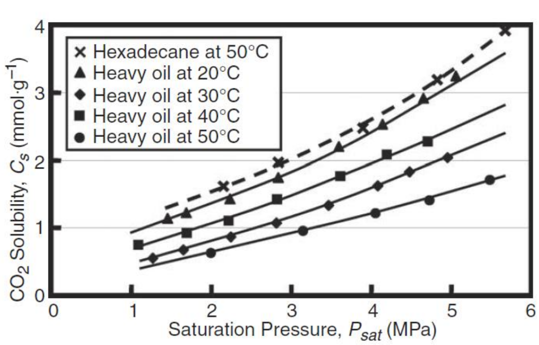

Fig. 2. Solubility of carbon dioxide in oil samples

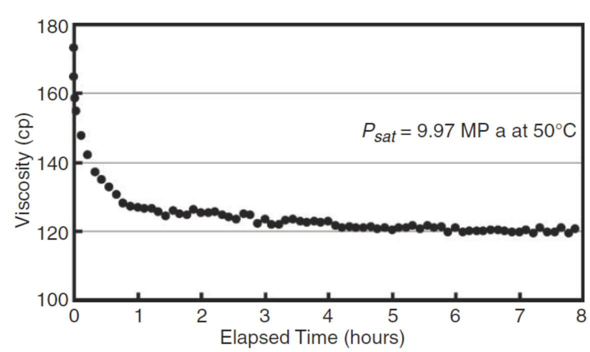

Fig. 3. Effect of carbon dioxide on oil viscosity

Another experimental study was conducted to measure the swelling of oil due to CO_2 dissolution [11]. The test oil sample was a heavy oil with a specific gravity of 0.97 and viscosity of 4,510 cP at 25°C. Test results in Fig. 4 show that oil volume increased by more than 6% due to carbon dioxide dissolution. Besides, the viscosity of the heavy oil significantly reduced, as shown in Fig. 5.

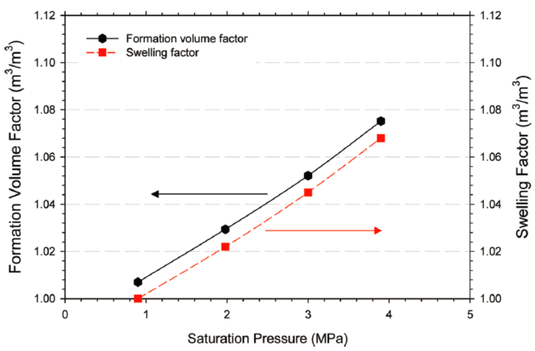

Fig. 4. Effect of carbon dioxide on oil swelling

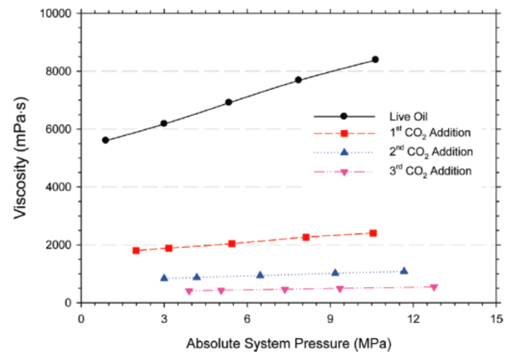

Fig. 5. Effect of carbon dioxide on the viscosity of extra heavy oil

After carbon dioxide is mixed with water, the pH of water decreases due to the production of carbonic acid, even though the majority of carbon dioxide stays in the aqueous phase as carbon dioxide molecules. While carbonated water migrates in the reservoir, carbonic acid, even though being weak, reacts with rock matrix and results in an increase in rock permeability [12]. It was reported that permeability of limestone cores improved by more than 10% after carbonated water injection [13].

3. Oil recovery tests with CWI

At Shell Oil Company, the research on CWI began in the 1960s. A number of sand pack tests were conducted at 120ºF and various pressures. The sand packs were either 3 ft long or 8 ft long. The viscosity of two oil samples was 10.7 and 57.4 cP. It was reported that CWI improved oil recovery by 4.5% for the 10.7 cP oil, and 13% for 57.4 cP oil.

In 1986, Shell conducted CWI tests with cores from Denver unit and crude oil from south Texas. The tests were conducted at 2,500 psi and 120ºF. It was revealed that CWI improved oil recovery by 18%. Oil swelling was recognized as the EOR mechanism, with swelling factor reaching 1.3.

In 2011, Shell Oil Company reported new test results on CWI. Carbonated water was injected into eight sand packs at varied injection velocities. The sand packs were 1.35 inch in diameter and 1 ft in length. The porosity of the sand packs were around 30%, and the permeability ranged from 2 to 4 Darcy. The crude oil samples had a specific gravity of 0.937 and viscosity of 70.7 cP under test conditions. The tests were carried out at 600 psi and 104ºF, and the injection rates were controlled at 1, 2, 4, and 15 pore volume/day. The CO_2 solubility was reaching 100 scf/stb under experimental conditions. The recovery was very high (80%) at a high injection rate, but the authors claimed that displacement became unstable at very high injection rate. Under injection velocity similar to field conditions, oil recovery improved by 9% [14].

At Herriot Watt University, carbonated water was injected in a rock sample obtained from North Sea field. The porosity and permeability or the cores were 0.35 and 4.58 Darcy, respectively. The core was injected with brine and subsequently carbonated brine. The brine composition was similar to the brine being injected in the North Sea field. Core flood tests were carried out at 2,500 psi and 100ºF. The tests revealed CWI improved oil recovery by 9% [15]. The authors also estimated that 11 million tonnes of carbon dioxide per year could be stored in the North Sea offshore fields.

4. Field cases of CWI

Oil Recovery Corporation carried out 6 CWI projects in the 1960s, with four being in Oklahoma, one in Kansas and one in Texas [16]. The field data is given in Table 2. The injection involved four steps. Firstly, liquefied butane was injected into wells to trigger a flood. Secondly, carbonated water containing a low concentration of surfactants was injected. Thirdly, CWI continued without surfactants. Finally, plain water was injected in the final phase.

Table 2. Field information for CWI projects

Field Name	Location	Reservoir depth (ft)	Average reservoir permeability (md)	Average reservoir porosity	Oil gravity (API)
K&S	Oklahoma	1,300	56	0.18	33
Wirt	Oklahoma	Not reported	44	0.16	33
Post Oak	Oklahoma	Not reported	43	0.17	35
White and Baker	Texas	1,750	24	0.21	31
Dome	Oklahoma	1,850	22	0.15	32

4.1. K&S Field

The K&S project was the first commercial CWI project. The 240 acre pilot was located near Bartlesville, Oklahoma. The field began production in 1905. The producing formation was sandstone at a depth of 1,300 ft. The detailed reservoir parameters are presented in Table 2. Before the CWI project started, the field had produced 512 thousand barrels of crude oil, and the oil production was only 30 BPD (barrels per day). The CWI project started in April 1958, involving 35 injection wells and 24 production wells. By late 1959, oil production rose from 30 to 2,300 BPD. Until early 1962, the oil rate was still above 600 BPD, as shown in Fig. 6.

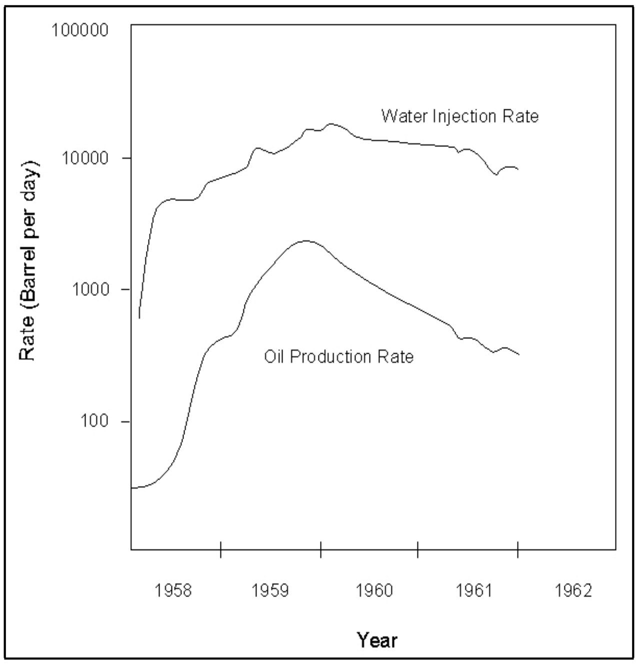

Fig. 6. Production history of K&S field

Water injection also improved. The water injection was initially 10 BPD per well. After CWI, the water injection rate rose to 700 BPD per well, and this improvement in injectivity lasted more than two years. It was observed that CWI not only improved rock permeability but also reduced bacteria that caused slime in the reservoir.

4.2. Wirt Field

The Wirt field is located north to the K&S project. CWI was initiated in March 1959. Within one year, the field oil production from four production wells increased continuously from 15 BPD to a peak of 420 BPD. Improved injectivity was also observed. The water injection rate climbed from 700 BPD to 1,500 BPD.

4.3. Post Oak Field

The post oak pilot lies to the south of the K&S pilot. Carbonated water was injected into 5 wells that control an area of 240 acres [17]. The CWI operation was started in April 1960, when the field was producing oil at 300 BPD. Within one year, the oil rate climbed to 870 BPD. Meanwhile, the water injection rate steadily increased from 2,500 BPD to 10,000 BPD.

4.4. White and Baker field

The 1,170-acre White and Baker pilot was located in Pecos County in Texas. The pilot involved 31 production wells and 16 injection wells. The field suffered from low injectivity. Before CWI, each injection well was receiving 100 BPD of water on average, and the oil production rate was only 150 BPD of oil. After CWI started in November 1960, water injection rate and oil production rate started to increase immediately. Unfortunately, very limited data was reported for this project.

For the K&S project, Wirt field and post oak project, carbon dioxide was supplied by on-site generating plants. Natural gas was burnt in boilers to produce flue gas containing 10% carbon dioxide. Carbon dioxide was extracted by the absorption process, then compressed, dried, and transported to wells through the pipeline.

While for the White and Baker project, carbon dioxide was purchased from a gas liquefaction plant, where carbon dioxide was removed from the natural gas produced from the Pecos County in Texas. The liquid carbon dioxide was then transported in insulated tanks to the storage facilities onsite.

4.5. Dome Field

The dome unit is located near Bartlesville in Oklahoma. The field started producing in 1910. Till 1961, it was estimated that 1.255 million barrels of oil had been produced. The daily oil production before CWI was 7-10 BPD.

CWI started in October 1961. Before initiation of CWI, each well was treated with 500 gallons of propane and 25 gallons of detergent. Water was injected through 2–inch tubing run to the bottom of the well. Liquid carbon dioxide was injected through half-inch tubing concentric to the 2-cinch tubing. Water and carbon dioxide mixed at the bottom of the well before entering the rock formations. About 5,000 tons of carbon dioxide was injected [18].

Production rate responded quickly to injection of carbonated water. In November 1961, oil production climbed to 448 BPD. In January 1962, oil production peaked at 740 BPD. Despite the good responses in production rates, the oil recovery was lower than expectation. Well, tests indicated that some wells had been fractured. It was believed that the injected carbonated water channeled through fractures, without effectively sweeping the oil in place.

4.6. Reservoir treatments with CWI

In the 1950s and 1960s, more than 300 wells in Oklahoma, Kansas, and Texas received carbonated water treatments to improve injectivity. Among these well, 225 wells received high-concentration carbonated water, while 70 wells were treated with low-concentration carbonated water [19].

For example, wells G-2 and G-3 in Kansas were treated with CWI. The production sandstone was 12.7 ft in thickness located at a depth of 790 ft. The reservoir porosity and permeability were 20% and 32 md, respectively. Before CWI, water injection rates declined to 22 BPD for well G-2 and 4 BPD for well G-3 due to scale problems. CWI started in October 1962. Both wells responded quickly. In November 1962, water injection climbed to 105 BPD and 57 BPD for well G-2 and G-3, respectively.

5. Conclusions

Carbonate water injection can be a good alternative to CO_2 flooding if the supply of CO_2 is limited. CWI improves oil recovery by swelling oil volume and reducing oil viscosity. Laboratory studies demonstrated CO_2 could significantly reduce the viscosity of heavy oil. Several CWI projects were carried out in USA. CWI improved both oil production and water injection. In conclusion, CWI has good potential for industrial application as an effective EOR method.

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