# EXPERIMENTAL STUDY OF CO2 STORAGE IN WATER-FLOODED OILFIELDS

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## ABSTRACT

$CO_2$ is the main source of greenhouse emission, and the environment problem caused by greenhouse effect has drawn worldwide attention. Meanwhile the method of waterflooding has been used in most oilfields in China. The $CO_2$-injection to the water-flooded oilfields will not only store $CO_2$, but also enhance the oil recovery. In this article, core flood tests with refined oil were conducted to investigate the $CO_2$ displacement characteristic in water-flooded oil reservoir under different formation pressure and oil saturation, and the $CO_2$ storage capacity was calculated. The tests result shows that the $CO_2$ injection can enhance the oil recovery about 15% OOIP under experimental conditions. When injecting $CO_2$ after waterflooding, the $CO_2$ storage capacity is increased as the formation pressure increase. The core flood tests also indicate that when the initial oil saturation of reservoir prior $CO_2$ injection is higher, the oil recovery will be higher when injecting the same PV of $CO_2$, and the $CO_2$ storage capacity is getting larger.

## INTRODUCTION

$CO_2$ is the main source of greenhouse emission, and the environment problem caused by greenhouse effect has drawn worldwide attention [1]. A great number of studies deal with $CO_2$ storage, including $CO_2$ EOR and $CO_2$ storage in saline or seawater aquifers, but few researches talk about $CO_2$ storage in water-flooded oilfields. Waterflooding is widely used in China and many oilfields are in high water cut stage, which has reached the limit of waterflooding from an economy perspective. Comparing with saline aquifers, there are completed injection-production infrastructures in waterflooding oilfields, and the reservoir conditions are better understood. Injecting $CO_2$ into the reservoirs can enhance oil recovery significantly (10% to 15%) [2, 3], It is beneficial for the situation of China particularly. Formation pressure, oil saturation and minimum miscibility pressure (MMP) are the main parameters to determine the $CO_2$ displacement efficiency and $CO_2$ storage capacity [1]. In this study, core flood tests have been conducted to evaluate the feasibility of $CO_2$-EOR after waterflooding under reservoir conditions. The formulae have also been derived to calculate the $CO_2$ storage capacity under different formation pressure and oil saturation.

## EXPERIMENT

### Core Sample and Fluids

The Chuan1 sandstone outcrops from SiChuan in China were used in the experiment, its petrophysical parameters are listed in Table 1. The refined oil (Caltex White Oil Phamra) was used, it was degassed by vacuum and its viscosity is 4.7 cP at 60 degC. The brine was NaCl solution with the salinity of 20.000 ppm. The purity of injecting $CO_2$ was 99.93%.

**Table 1. Petrophysical Parameters of Core Samples and Test Type**

| Sample No. | Porosity % | PV $cm^3$ | Length cm | Area $cm^2$ | $K_{air}$ mD | Test type |
|---|---|---|---|---|---|---|
| C1-B14 | 12.8 | 20.903 | 29.73 | 5.50 | 30.0 | Use in different pressure test |
| C1-B14 | 11.8 | 19.301 | 29.73 | 5.50 | 28.4 | Repeat use in different pressure test |
| C1-B51 | 13.2 | 20.794 | 29.50 | 5.32 | 30.5 | Use in different pressure test |
| C1-B07 | 12.2 | 20.202 | 29.95 | 5.54 | 22.4 | Repeat use in different saturation |

### Experiment Set-up and Procedure

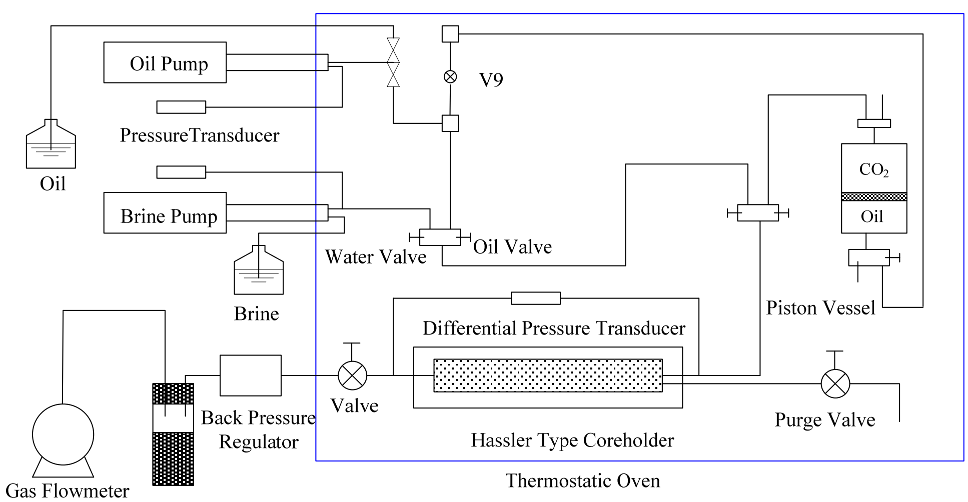


**Figure 1. Schematic of $CO_2$ Flooding Test**

The experimental schematic is shown in Figure 1. A Hassler type coreholder was used, it was set in a horizontal position. Production of oil/brine/$CO_2$ was measured by volumetric method, the experimental temperature was 60 degC and the effective overburden pressure was 3MPa. Injection rates for water and $CO_2$ were 1.0ml/min and 0.5ml/min respectively. The key steps of the coreflood experiment are as follows: first the cores were saturated with brine, and irreducible water saturation was established by oil displacement in rates 0.1ml/min to 2.0ml/min. Subsequently, water flooding was conducted until water cut in the core reached 99.9%. Finally $CO_2$ was injected in 3-3.5PV. Estimated saturation accuracy is better than 2%.

## RESULTS AND DISCUSSION

### $CO_2$-Injection Experiment after Waterflooding under Different Formation Pressure

One can see from Figure 2 that injection pressure keeps increasing at early stage during both waterflooding and $CO_2$ flooding process, except that 20MPa back pressure during waterflooding. After breakthrough, the pressure decreased and was stable in the late stage. When injecting $CO_2$ after waterflooding, the amount of produced oil was little before $CO_2$ breakthrough. After that, oil recovery was increasing gradually, and simultaneously, gas/oil ratio increased promptly. $CO_2$-EOR is increased as the back pressure increase.

**Table 2. $CO_2$ Displacement Efficiency at Different Back Pressure**

| Sample No. | Initial water saturation | $CO_2$ Injected | Waterflood Efficiency | $CO_2$ EOR | Final Displacement Efficiency | $CO_2$ Saturation | Back Pressure |
|---|---|---|---|---|---|---|---|
| | % | PV | %OOIP | %OOIP | %OOIP | % | MPa |
| C1-B14 | 59.1 | 3.12 | 38.6 | 15.2 | 53.8 | 25.2 | 10 |
| C1-B14 | 56.4 | 3.13 | 41.3 | 15.4 | 56.7 | 27.4 | 15 |
| C1-B51 | 58.8 | 3.35 | 42.3 | 17.7 | 60.0 | 30.5 | 20 |

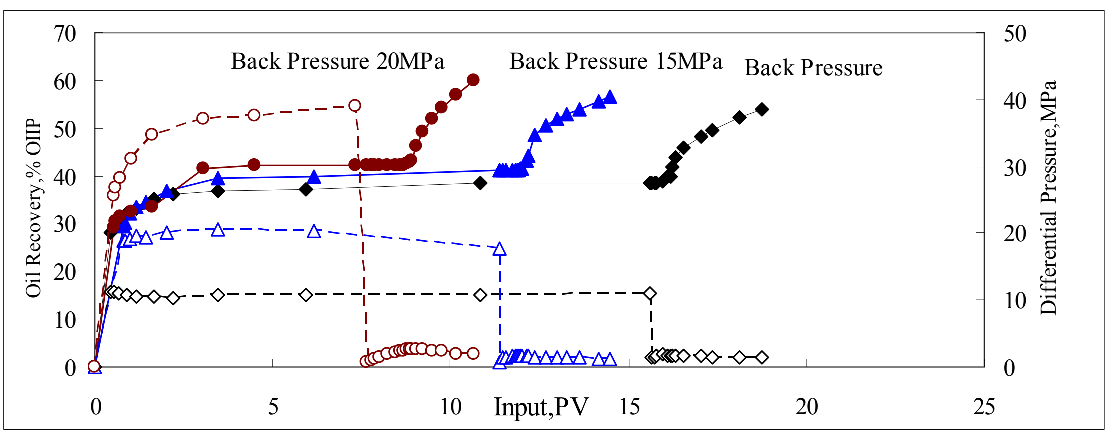


**Figure2. Oil Recovery and Differential Pressure as Function of Volume Injected**

Table 2 shows that $CO_2$ storage capacity increases accompanied by water and oil production. The higher the back pressure is, the higher the saturation of $CO_2$ is, and the higher the oil recovery and produced liquid recovery of $CO_2$ flooding will be. The $CO_2$-injection PV were similar in the three experiments, so it can be concluded that the utilization efficiency of $CO_2$ will be high when the back pressure is high.

### $CO_2$-Injection Experiment after Waterflooding at Different Oil Saturation

Table 3 shows that for the first experiment, the displacement efficiency by complete waterflooding was 33.6%, and the total recovery of following $CO_2$ flooding was 45.6% OIIP. No waterflooding process was carried out for the second experiment, and the displacement efficiency of $CO_2$ flooding under irreducible water saturation condition was 68.4% OIIP, which was obviously higher than that of the first experiment. When injecting the same PV of $CO_2$, the higher the oil saturation before $CO_2$ flooding is, the higher the final displacement efficiency is, as well as the larger the amount of $CO_2$ trapped and the higher the $CO_2$ saturation.

**Table 3. $CO_2$ Displacement Efficiency at Different Oil Saturation**

| Test Sequence | Sample No. | $S_{wi}$ | $S_o$ Before $CO_2$ Flooding | $CO_2$-Injection PV | Total Efficiency | $CO_2$ Saturation |
|---|---|---|---|---|---|---|
| | | % | % | PV | %OOIP | % |
| 1 | C1-B07 | 21.2 | 50.0 | 3.79 | 45.6 | 27.0 |
| 3 | C1-B07 | 21.8 | 67.5 | 3.49 | 62.6 | 29.7 |
| 2 | C1-B07 | 16.9 | 83.1 | 3.43 | 68.4 | 56.8 |

## CALCULATION OF $CO_2$ STORAGE CAPACITY

Hitchon (1996) proposed that there were three $CO_2$ storage mechanisms in the aquifers: hydrodynamic, dissolution and mineral trapping [4]. This applies to the mechanism of $CO_2$ storage in water-flooded oilfields. Mineral trapping requires a substantial long period of time, which has little contribution to achieve $CO_2$ storage in a short time. If the mineralization reaction between $CO_2$ and rock or ions in the brine is not considered, the $CO_2$ storage capacity is the sum of hydrodynamic and dissolved trapping. In the coreflood experiment after waterflooding, $CO_2$ replaces the displaced liquid to occupy the volume in the core. $CO_2$ is trapped in the core as gas or supercritical state, and the amount of this part is called Trapped Storage Capacity. There might be some $CO_2$ dissolved into the remaining oil and water after $CO_2$ flooding, and the dissolved amount is also one part of $CO_2$ storage capacity which is called Dissolved Storage Capacity. The $CO_2$ solubility in the oil was determined by flash separation experiment, as well as volume factor of oil. In addition, the solubility and volume factor of $CO_2$ in the brine was calculated by the theoretical formula given by Duan Zhenhao[6]. Total $CO_2$ Storage Capacity is the sum of trapped and dissolved storage capacity and can be calculated by the formula (1):

$$M_{CO2(P,T)} = \rho_{CO2(P,T)} V_o B_o + \rho_{CO2(P,T)} V_w B_w + V_{ro} R_{oCO2} + V_{rw} R_{wCO2} \quad (1)$$

Where， $\rho_{CO2(P,T)}$ is $CO_2$ density, g/cm$^3$; $V_o$,$V_w$ is displaced oil and water volume, ml; $B_o$, $B_w$ is oil and water volume factor, defined as the change of liquid volume caused by the difference of the temperature and pressure in and out of the core. $R_{oCO2}$, $R_{wCO2}$ is $CO_2$ solubility in oil and water, g/cm$^3$, $V_{ro}$, $V_{rw}$ is the remaining oil and water volume, ml.

**Table 4. $CO_2$ Storage Capacity after Waterflooding under Different Pressure**

| Sample No. | Back Pressure | CO2 Saturation | Trapped Storage Capacity | Dissolved Amount in Water | Dissolved Amount in Oil | Total Storage Capacity | Storage Capacity |
|---|---|---|---|---|---|---|---|
| | MPa | % | g | g | g | g | g/cm$^3$ |
| C1-B14 | 10 | 25.21 | 2.991 | 0.182 | 1.539 | 4.712 | 0.225 |
| C1-B14 | 15 | 27.36 | 6.292 | 0.140 | 1.831 | 8.263 | 0.409 |
| C1-B51 | 20 | 30.54 | 8.226 | 0.183 | 2.519 | 10.928 | 0.526 |

**Table 5. $CO_2$ Storage Capacity after Waterflooding at Different Oil Saturation**

| Sample No. | Oil Saturation | $CO_2$ Saturation | Trapped Storage Capacity | Dissolved Amount in Water | Dissolved Amount in Oil | Total Storage Capacity | Storage Capacity |
|---|---|---|---|---|---|---|---|
| | % | % | g | g | g | g | g/cm$^3$ |
| C1-B07 | 50.0 | 27.0 | 3.342 | 0.323 | 2.360 | 6.025 | 0.298 |
| C1-B07 | 67.5 | 29.7 | 3.413 | 0.251 | 2.342 | 6.007 | 0.320 |
| C1-B07 | 83.1 | 56.8 | 6.449 | 0.150 | 1.438 | 8.037 | 0.434 |

Table 4 shows that the trapped storage capacity is the main part of the total storage capacity in the core. Under three back pressure conditions, the $CO_2$ trapped storage capacity is 63.5%, 76.2% and 75.3% of the total storage capacity respectively, while the amount of $CO_2$ dissolved in the remaining oil and water is little. So the displacement efficiency is the main factor to determine the $CO_2$ storage capacity.

The oil saturation is different in the reservoir at a different waterfooding stage, and the $CO_2$ storage capacity and recovery are affected by the initial oil saturation before $CO_2$

injection. The $CO_2$ storage capacity after $CO_2$ flooding at different oil saturation stage is given in Table 5. The result shows that the higher the oil saturation is, the higher the remaining $CO_2$ saturation is, and the larger the amount of trapped $CO_2$ is. The trapped storage capacity is 55.5%, 56.8% and 80.2% of the total storage capacity, which occupies a majority of the total amount. The amount of $CO_2$ dissolved in the remaining oil ranks the second, and the amount of $CO_2$ dissolved in the remaining water is the smallest part of the total. It can be concluded that the $CO_2$ displacement efficiency and remaining oil saturation are the main factors to determine $CO_2$ storage capacity.

## CONCLUSIONS

When injecting about 3PV $CO_2$ after waterflooding, $CO_2$ can effectively improve oil recovery by about 15% OOIP. The higher the formation pressure is, the higher the oil recovery is, and the larger the $CO_2$ storage capacity will be. The higher the initial oil saturation before $CO_2$ flooding is, the higher the oil recovery and the total liquid recovery is, and the larger the $CO_2$ storage capacity will be when injecting the same PV of $CO_2$. The displacement efficiency of $CO_2$ flooding is the main factor to determine capacity of $CO_2$ storage. The trapped storage capacity of $CO_2$ ranges from 55.4% to 80.2% to the whole storage capacity. Water-flooded oil reservoirs are the ideal place for $CO_2$ storage. It is thus beneficial in improving oil recovery, storing $CO_2$ and relieving the greenhouse effect.

## ACKNOWLEDGEMENTS

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