EXPERIMENTAL STUDY OF ENHANCE OIL RECOVERY USING GREENHOUSE GASES

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Abstract—CO\textsubscript{2} as the main cause of global warming is threatening the circumstance of human being living. So the geological storage of CO\textsubscript{2} becomes one of the hot topics. By physics simulation experiments, the feasibility study of enhance oil recovery (EOR) using CO\textsubscript{2} is studied. The results show that CO\textsubscript{2} can not only enhance the recovery percent, but also can be stored in reservoir effectively. CO\textsubscript{2} can greatly increase oil recovery percent compared with water flooding. Water alternating CO\textsubscript{2} should given priority by using CO\textsubscript{2}. In case of water alternating CO\textsubscript{2} the optimum gas water ratio is 1:1 and the optimum plug volume is 0.1 times of pore volume (PV), earlier water alternating CO\textsubscript{2} will makes better development effect.

Index Terms—Greenhouse gases, CO\textsubscript{2}, Enhance oil recovery, Physics simulation

I. INTRODUCTION

Because of the over-reliance on fossil fuels (coal, oil and natural gas), the emission of CO\textsubscript{2} by industry and living has been increased, which has destroyed the environment more and more seriously. Among many greenhouse gases, more than 65% is CO\textsubscript{2} [1,2]. The storage of CO\textsubscript{2} mainly chooses depleted reservoir, deep brine reservoir, unworkable coal bed and deep sea etc, which is an efficient way to avoid the global warming [3-6]. The ARI company study three CO\textsubscript{2} gas reservoirs show that CO\textsubscript{2} can storage for millions of years. In July 2005, the feasibility study of CO\textsubscript{2} storage by IEA in the Weyburn oil field show that only 0.02% of CO\textsubscript{2} used to drive displacement is escaped from the reservoir in 5000 years, most of them get into the cap rock and can not invaded the drinking water aquifers, escaped quantity from the oil and water Wells is lower than the 0.001% of the original reserves [7-9]. The results suggest that CO\textsubscript{2} flooding can greatly enhance the oil recovery efficiency [10-12]. Due to the well sealing, the reservoir can realize CO\textsubscript{2} geological storage for a long time. Using CO\textsubscript{2} as a drive force can not only increase the crude oil recoverable reserves, also realize long-term CO\textsubscript{2} geological storage, which realizes the social benefit of CO\textsubscript{2} emission reduction and enormous economic benefits.

Since 1952 Whorton got the first patent of carbon-dioxide flooding—“EOR by CO\textsubscript{2} flooding” has been thought much by the practical operators as a secondary method to improve oil recovery after water flooding. The CO\textsubscript{2} EOR technology is getting innovated and matured depend on the sustained and stable air supply which contain a lot of CO\textsubscript{2}. Holm summarized the CO\textsubscript{2} flooding mechanism systematically for dissolved gas flooding, immiscible flooding, first and multiple injection by industry and living has been increased, which has destroyed the environment more and more seriously. Among many greenhouse gases, more than 65% is CO\textsubscript{2} [1,2]. The storage of CO\textsubscript{2} mainly chooses depleted reservoir, deep brine reservoir, unworkable coal bed and deep sea etc, which is an efficient way to avoid the global warming [3-6]. The ARI company study three CO\textsubscript{2} gas reservoirs show that CO\textsubscript{2} can storage for millions of years. In July 2005, the feasibility study of CO\textsubscript{2} storage by IEA in the Weyburn oil field show that only 0.02% of CO\textsubscript{2} used to drive displacement is escaped from the reservoir in 5000 years, most of them get into the cap rock and can not invaded the drinking water aquifers, escaped quantity from the oil and water Wells is lower than the 0.001% of the original reserves [7-9]. The results suggest that CO\textsubscript{2} flooding can greatly enhance the oil recovery efficiency [10-12]. Due to the well sealing, the reservoir can realize CO\textsubscript{2} geological storage for a long time. Using CO\textsubscript{2} as a drive force can not only increase the crude oil recoverable reserves, also realize long-term CO\textsubscript{2} geological storage, which realizes the social benefit of CO\textsubscript{2} emission reduction and enormous economic benefits.

II. EXPERIMENTAL SECTIONS

A. Experimental Conditions

Oil sample used in this study was prepared by using dead oil and natural gas. The purity of CO\textsubscript{2} used in these experiments is 99.999% (Beiwen, China). The simulating formation water with the same ion concentration as the underground fluid in the oilfield is used as the displacing fluid. Five natural cores are used in this study, which are sequenced follow a certain order. The assembled core has a length of 29.23cm and a porosity of 14.15%. Diameter of the assembled core is 2.5cm and the permeability is 1.76x10^-3 m². Experimental temperature is set as 85°C.

B. Materials & Conditions

In this paper, a self-developed experimental platform is established, and the schematic diagram of the experimental flow system, as is shown in Figure 1, consists mainly of the following devices: (1) Three high pressure stainless-steel cylinders (0-70MPa; ≤150°C, 200-1000mL; Huaan, China) were used to store and deliver oil, water and CO\textsubscript{2} samples. (2) A date acquisition system was used to get the temperature date and pressure date for real-time. (3) A back pressure pump and a confining pressure pump were used to maintain the pre-specified pressure inside the cell during the tests (Huaan, China; pressure range, 0-5800 psi; pressure accuracy, 0.1%). (4) A syringe pump (ISCO, flow range, 0.001-60 mL/min; flow accuracy, 0.5%; pressure range, 0-10000 psi; pressure accuracy, 0.1%) was used to displace samples (oil, CO\textsubscript{2} and water). (5) A core holder (0-100MPa; ≤150°C; Huaan, China) was used to realize the core which can be compressed same as reservoir conditions. (6) A wet type gas flow meter (volume, 2 liters per revolutions; volume accuracy, 1% ; Changchun, China) was used to measure the volume of a gas.

![Fig. 1. Schematic of the experimental setup](image_url)
C. **Experimental Procedures**

Experimental studies were carried out using three different driving methods, which were water flooding, CO₂ flooding and WAG respectively. Three different driving methods share the same experimental procedures as follows: (1) The cores were cleaned and dried at first. Then they were assembled to a long core. (2) To remove the gas in the core by pulling a vacuum on it, and then it was saturated by simulating formation water. (3) Oil displacing water was carried out at the speed of 0.5cc/min last for 20PV. The irreducible water saturation was calculated based on the date which come from the above experiment. (4) Experiments were carried out using different driving methods. Fluid volume (oil, water and gas) and upstream/downstream pressure were recorded. (5) The cores were cleaned and dried after the experiment. Repeat the above-mentioned steps to perform different experiment.

### III. RESULTS AND DISCUSSION

#### A. Water Flooding Experiment

It is clear from Figure 2 that water breakthrough when the injection volume reaches 0.31 times of pore volume (PV), the water breakthrough recovery percent (RP) is 39.34%. After water breakthrough, water cut shows rapidly increase and it costs 0.35PV to make the water cut reaches 90%. The ultimate recovery percent (URP) of water flooding is 51.56%.

It can be seen from Figure 3 that the experimental core has high injection pressure, which is 39.09MPa on average. The injection pressure increases as the injection volume increase, after the injection volume reaches 0.6 PV, the injection pressure falls with a slow rate. Therefore water injection is difficult to carry out in the target reservoir.

#### B. CO₂ Flooding Experiment

As seen in Table 1, the injection volume at gas breakthrough, RP at gas breakthrough and URP increase along with the injection rate increase.

<table>
<thead>
<tr>
<th>Injection rate (cc/min)</th>
<th>Injection pressure at gas breakthrough (MPa)</th>
<th>RP at gas breakthrough (%)</th>
<th>URP (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>0.61</td>
<td>17.21</td>
<td>72.91</td>
</tr>
<tr>
<td>0.5</td>
<td>0.72</td>
<td>18.34</td>
<td>76.23</td>
</tr>
<tr>
<td>1.0</td>
<td>0.73</td>
<td>22.45</td>
<td>78.32</td>
</tr>
<tr>
<td>1.5</td>
<td>0.76</td>
<td>24.44</td>
<td>79.74</td>
</tr>
<tr>
<td>2.0</td>
<td>0.81</td>
<td>30.67</td>
<td>80.24</td>
</tr>
</tbody>
</table>

It can be seen from Figure 4 that the RP increases along with the increase of CO₂ injection volume and injection rate. That is mainly because higher injection rate will lead to higher injection pressure, thus more CO₂ is dissolved in oil, due to which the oil viscosity and the interface tension reduces and the flooding is much more close to miscible flooding. Figure 5 shows that CO₂ breakthrough when the injection volume reaches 0.6PV and the gas-oil ratio (GOR) begin to increase slowly. GOR shows rapidly increase after the injection volume reaches 1.2PV. It can be seen from Figure 6 that injection pressure increases as the increase of injection volume before CO₂ breakthrough. CO₂ injection pressure shows significant decrease after CO₂ breakthrough. Higher injection rate can lead higher injection pressure. It can be seen from Figure 7 that in case of higher injection rate, more CO₂ injection volume is needed to make CO₂ breakthrough and the breakthrough RP is higher as well.
(2) Slug Size Optimization Experiment
In this experiment, the injection rate is 0.5 cm$^3$/min, and the WGR is 1:1. Five slug sizes (0.05PV; 0.1PV; 0.2PV; 0.3PV; 0.4PV) are designed.

As seen in Table 3, the injection volume at gas breakthrough and the injection volume at water breakthrough decreases along with the slug size increase. The slug size is 0.2PV with the maximum URP.

### TABLE 2 WAG experimental results at different water gas ratio

<table>
<thead>
<tr>
<th>WGR (m$^3$/m$^3$)</th>
<th>Injection volume at water breakthrough (PV)</th>
<th>RP at water breakthrough (%)</th>
<th>URP (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:3</td>
<td>2.92</td>
<td>50.24</td>
<td>78.32</td>
</tr>
<tr>
<td>1:2</td>
<td>1.37</td>
<td>55.17</td>
<td>77.71</td>
</tr>
<tr>
<td>1:1</td>
<td>1.13</td>
<td>52.46</td>
<td>79.91</td>
</tr>
<tr>
<td>2:1</td>
<td>0.92</td>
<td>32.03</td>
<td>76.40</td>
</tr>
<tr>
<td>3:1</td>
<td>0.88</td>
<td>9.34</td>
<td>75.41</td>
</tr>
</tbody>
</table>

(3) Alternating Timing Optimization Experiment
In this experiment, the injection rate is 1.0 cm$^3$/min, and the WGR is 1:1. The slug size is 0.1PV. The alternating timing refers to the volume of CO$_2$ which have been injected in the core before WAG experiment.

### TABLE 4 WAG experimental results at different alternating timing

<table>
<thead>
<tr>
<th>Alternating timing</th>
<th>Injection volume at water breakthrough (PV)</th>
<th>RP at water breakthrough (%)</th>
<th>URP (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>1.17</td>
<td>43.25</td>
<td>83.68</td>
</tr>
<tr>
<td>0.2</td>
<td>1.38</td>
<td>37.89</td>
<td>82.77</td>
</tr>
<tr>
<td>0.3</td>
<td>1.55</td>
<td>35.56</td>
<td>85.68</td>
</tr>
<tr>
<td>0.4</td>
<td>1.81</td>
<td>31.47</td>
<td>81.65</td>
</tr>
<tr>
<td>Breakthrough</td>
<td>2.13</td>
<td>32.95</td>
<td>86.21</td>
</tr>
</tbody>
</table>

At first, in this experiment, the core was injected CO$_2$ with the volume of 0.1PV, 0.2PV, 0.3PV, 0.4PV and CO$_2$ breakthrough respectively as five different alternating timings. As seen in Table 4, the earlier the alternating timing is, and the latter gas breakthrough and the earlier water breakthrough. The URPs of different alternating timings are close.

### IV. CONCLUSIONS

1) Environmental problems caused by CO$_2$ emissions have caught much attention worldwide. Combining CO$_2$ storage with EOR can not only make profit for oil companies but also lead to a contribution to the environment. Thus further researches on CO$_2$ flooding in oil extraction are strongly needed.

2) URP of water flooding is 51.56%, and that of CO$_2$ flooding is 72.91%-80.24%.

3) RP of CO$_2$ flooding increases along with the increase of injection CO$_2$ volume. Increasing rate of CO$_2$ flooding recovery slows down after the CO$_2$ breakthrough. CO$_2$ flooding RP increases as the increase of injection rate. Once the injection rate increases, the CO$_2$ breakthrough time delays and the breakthrough recovery increases. CO$_2$ injection pressure increases as the increase of injection volume, the injection volume increases and injection pressure significantly reduces after CO$_2$ breakthrough. CO$_2$ flooding reaches better development effect under high injection rate and pressure.

4) Earlier water alternating CO$_2$ leads to higher injection pressure and production rate, the water breakthrough time also become earlier while the CO$_2$ breakthrough time delays, and higher recovery percent will finally made.

5) Water alternating CO$_2$ should given priority when using CO$_2$ flooding. In case of water alternating CO$_2$, the
optimum WGR is 1:1 and the optimum plug size is 0.1PV, earlier water alternating CO$_2$ will make better development effect.

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