RESEARCH ON CO₂ FLOODING FOR IMPROVED OIL RECOVERY IN WATER FLOODING ABANDONED RESERVOIRS

Baolun Niu*, Ruijian Deng¹, Yiqing Lin², Zhang Zhang¹, Changhua Yang¹, Xun Zhou¹, Shaoran Ren³, and Zhaomin Li³

¹ Production Engineering and Technology Institute, Zhongyuan Oilfield Branch Company, Sinopec, Puyang, Henan 457001, P. R. of China
² School of Foreign Languages, Xi’an Shiyou University, Xi’an, Shaanxi Province, 710065, P. R. China
³ School of Petroleum, China University of Petroleum, Qingdao, Shandong province, 266550, PR of China

ABSTRACT

CO₂ injection is an effective technique for improved oil recovery in light oil reservoirs, especially for water flooding abandoned reservoirs. In this study, the lower part of Es1 reservoirs in Pucheng oilfield was introduced as the target reservoir. By studying the minimum miscible pressure in CO₂ flooding, the reservoir could achieve miscible flooding. Long core displacement experiments proved that water alternating CO₂ flooding could significantly improve the recovery. For the reservoir characteristics, anti-corrosion technology in the process of injection was researched, and the H-20 inhibitor was screened. A channeling blocking agent in combination with the delayed expansion of gel particles and cross-linked copolymer was used to control the gas fluidity. The Pu 1-1 well groups were optimized to conduct a field trial. The cumulative injected liquid CO₂ was 19219.95 t, 0.248 PV and the cumulative increasing oil was 4520.9 t. The predicted recovery will increase by 8.3%. The successful implementation of the project can provide technical attempt for completion of energy to succeed and energy-saving emission reduction targets.

Keywords: Gas Injection, IOR, Water Alternating CO₂ Injection, CO₂ Corrosion, CO₂ Foam

INTRODUCTION

CO₂ flooding has the advantage of lower miscible pressure and a wide variety of sources and can embody the concept of “green development”, which is one of the best methods for enhance oil recovery [1,2]. The way of water alternating CO₂ flooding into water flooding abandoned reservoirs has just beginning and this technology has been used in the lower part of Es1 reservoir in Pucheng oilfield. As the technology matures, water alternating CO₂ flooding can be prevalent in China and it can achieve the goal of energy-saving and emission-reduction.

The lower part of Es1 reservoirs in Pucheng oilfield is an equipped reservoir and the depth is from -2280 to -2437 m. The geological reserve is 1135×10⁴ t. The effective reservoir thickness is 5.3 m and the porosity is 28.1%. The average of permeability is 690 mD. The oil viscosity is 1.82 mPa.s and the water mineralization is 24×10⁴ mg/l. The temperature is 82.5 °C.
After long-term water flooding, the recovery achieved 50.04% in 1998, which has gone into the stage of high water cut of 98.44%. This reservoir came to abandoned stage in 1998, and all the wells were closed. The technology of water alternating CO₂ flooding was introduced in this reservoir in 2008.

RESULTS AND DISCUSSION

Experimental Results of CO₂ Flooding in Abandoned Reservoirs after Water Flooding

Research on MMP

The volume coefficient of oil in the lower part of Es1 reservoirs in Pucheng oilfield is 1.2356 at 82.5 °C and its saturation pressure is 9.83 MPa. Under the condition of reservoir, the density of oil is 0.7554 g/cm³, and the viscosity of oil is 1.987 mPa.s. The gas-oil ratio is 64.3 m³/m³.

The slim tube experiments show that the MMP is 18.42 MPa at 82.5 °C as seen in Figure 1. The pressure of the lower part of Es1 reservoirs in Pucheng oilfield is 20.02 MPa, which is higher than the MMP, and the CO₂ flooding can form miscible flooding.

![Figure 1: Slim tube experiments result of oil recovery at different pressures](image)

In Test-1, water flooding was first conducted up to 98% of water cut, and the recovery reached 57.6%. CO₂ flooding was followed with 0.4 pore volume (PV), and the final recovery was 88.51%, as shown in Figure 2.

In Test-2, water flooding was first conducted up to 98% of water cut, and the recovery reached 57.6%. Water alternating CO₂ flooding was followed. The volume of CO₂ achieved 0.4 PV and the final recovery was 93%, as shown in Figure 3. The experiments show that the water alternating CO₂ flooding could delay the gas channeling. Therefore, water alternating CO₂ flooding after water flooding was the optimal injection to obtain a higher recovery.

Experimental Results of Water Alternating CO₂ Flooding

Experimental conditions were as above the design of the water alternating CO₂ flooding into the long-core flooding tests contained 7 slugs of CO₂, and the total injected volume was 0.15 HPV. After water driving (water cut was greater
than 98%), the cumulative injection volume of \( \text{CO}_2 \) was 0.15 PV (7 cycles, each slug was 0.02 PV).

![Figure 3: Curves of oil recovery and GOR (gas production/oil production) during water alternation \( \text{CO}_2 \) flooding](image)

As shown in Figure 4, after water alternating \( \text{CO}_2 \) flooding, water cut was reduced significantly to 40.1%, and the recovery went up to 17.41% (reached 74.85%). The gas to oil exchange ratio was 0.88 ton/ton.

**Research on Anticorrosion during \( \text{CO}_2 \) Flooding**

It is difficult to solve the corrosion problem by selecting the materials of pipes, for the reason of galvanic corrosion between oil pipes and fixed casing pipes. Focus on the development of preferred corrosion inhibitor and the optimization of sacrificial anode material through their combination effectively solve the problem of \( \text{CO}_2 \) corrosion.

![Figure 4: Curves of oil recovery and water cut during water alternation \( \text{CO}_2 \) injection](image)

**Optimization of Corrosion Inhibitor**

Static immersion tests experiments were introduced by water from the production wells. Before the experiments, \( \text{CO}_2 \) was filled in 20 minutes. The temperature was 80 °C, and the pressure was 4.0 MPa. The material of specimen was N80 and the test period was 7 days. The execution of this experiment method was in accordance with the “oilfield produced water corrosion inhibitor performance evaluation method” (according to the China industry standard of SY/T 5273-2000). By way of evaluation of a variety of corrosion inhibitor, H-20 was selected as a high temperature \( \text{CO}_2 \) corrosion inhibitor and had a good inhibition effect; the concentrations used are listed in Table 1 and Figure 5.

<table>
<thead>
<tr>
<th>Concentration (mg/l)</th>
<th>Weight before test (g)</th>
<th>Weight after test (g)</th>
<th>Total weight loss (g)</th>
<th>Average weight loss (g)</th>
<th>Average rate of corrosion (mm/a)</th>
<th>Rate of corrosion inhibition (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>11.0162</td>
<td>10.914</td>
<td>0.1022</td>
<td>0.1030</td>
<td>0.7378</td>
<td>70.9</td>
</tr>
<tr>
<td>200</td>
<td>10.8771</td>
<td>10.7732</td>
<td>0.1039</td>
<td>0.1036</td>
<td>0.214558</td>
<td>93.5</td>
</tr>
<tr>
<td>500</td>
<td>10.9686</td>
<td>10.9247</td>
<td>0.0439</td>
<td>0.0436</td>
<td>0.214558</td>
<td>70.9</td>
</tr>
<tr>
<td></td>
<td>10.9973</td>
<td>10.9539</td>
<td>0.0434</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>11.0189</td>
<td>11.0095</td>
<td>0.0094</td>
<td>0.0096</td>
<td>0.0476</td>
<td>93.5</td>
</tr>
</tbody>
</table>

**Table 1: Optimization result of corrosion inhibitors**
Figure 5: Rate of corrosion at different temperatures and pressures

It could be concluded from Table 1 that there is a good inhibition effect when the concentration of H-20 corrosion inhibitor is greater than 200 mg/l.

Optimization of Sacrificial Anode Materials

In an allusion to the environment of high temperature and mineralization of the Zhongyuan oilfield, the experiments were carried out to optimize the anode material at 80 °C, as shown in Table 2 and Figure 6. Experimental methods reference the standards of China national standard of GB4948-2002 and GB/T17848-1999.

Table 2 and Figure 6 show that the result of the working potential and open circuit potentials of the A21 are more negative working potentials and the working potential slightly changes with time. The fluctuation range is narrow, and the working potential is relatively stable. The efficiency of current is comparatively high reaching 57.27%, and the surface dissolution is suitable for the media environment.

Research on Deep Profile and Anti-CO₂ Channeling

The lower part of Es1 pilot experiment area is a high permeability reservoir, which has maintained a relatively high production rate since its development; also, its severe large pores caused by water flooding are prone to gas channeling. In order to control the gas flow, the deep profile control system and gas channeling foam system are determined to be used through research [3,4].

Research on Deep Profile

In order to obtain a better effect of deep profile, a system containing the delayed expansion of gel particles and cross-linked copolymer has been developed.

<table>
<thead>
<tr>
<th>Number</th>
<th>Open Circuit Potential (V, vs. SCE)</th>
<th>Working potential (V, vs. SCE)</th>
<th>Specific consumption (kg/A-·a)</th>
<th>Actual capacitance (A·h/kg)</th>
<th>Current efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average value</td>
<td>Range</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A11</td>
<td>-1.014</td>
<td>-0.946 to -1.006</td>
<td>-0.980</td>
<td>3.2505</td>
<td>1240.425</td>
</tr>
<tr>
<td>A21</td>
<td>-1.008</td>
<td>-0.903 to -0.978</td>
<td>-0.958</td>
<td>1.8515</td>
<td>1633.27</td>
</tr>
<tr>
<td>R6</td>
<td>-1.019</td>
<td>-0.833 to -0.984</td>
<td>-0.929</td>
<td>6.658</td>
<td>760.08</td>
</tr>
</tbody>
</table>
The system not only overcomes the shortcomings of heat resistance of the crosslinking system, the harsh conditions of the gelling which is easily impacted by the mineralization, and low intensity, but also compensates for the shortcomings of the difficulty to enter into the tiny pores of formation and the dispersed phase to move forward in the formation of pre-crosslink particle gel system; this indicates that the system can achieve the effect of deep profile.

Three sand-packs with similar permeability were prepared. The first sand-pack was flooded by crosslinking agents (0.15 PV) and slow inflation particles (0.15 PV). The second sand-pack was flooded by slow inflation particles (0.3 PV). The third sand-pack was flooded by the system of crosslinked copolymer system.

The combined sealing effects of crosslinked copolymer and slow inflation particles were better than each system alone, and the oil recovery was significantly improved as shown in Table 3.

### Table 3: Sealing characteristics of crosslinking copolymer composite system

<table>
<thead>
<tr>
<th></th>
<th>1# sand-pack</th>
<th>2# sand-pack</th>
<th>3# sand-pack</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breakthrough pressure (MPa)</td>
<td>1.3</td>
<td>0.9</td>
<td>0.65</td>
</tr>
<tr>
<td>Recovery after plugging (%)</td>
<td>87.25</td>
<td>82.59</td>
<td>85.6</td>
</tr>
<tr>
<td>Incremental recovery (%)</td>
<td>12.5</td>
<td>7.01</td>
<td>9.36</td>
</tr>
<tr>
<td>Ratio of plugging (%)</td>
<td>90.3</td>
<td>87.7</td>
<td>73</td>
</tr>
</tbody>
</table>

Research on Anti-CO$_2$ Channeling

The foam has very unique characteristics of seepage flow in porous media, and Jamin effect on the gas has a strong channel blocking effect, which can effectively control the gas fingering. However, the characteristics of Zhongyuan oilfield such as high temperature, high salt, and high calcium and magnesium are bad for the stability of foam. From the laboratory study, a CO$_2$ channeling foam system named CY-I was screened to be adapted for high temperature and high mineralization reservoirs.

The blistering volume and half-life of CY-I system were tested by way of aeration and Ross-Miless (according to the China national standard of GB/T7462-94) at room temperature as shown in Table 4.

From the results of Table 4, it can be concluded that the CY-I system is compatible with injected water with a good sparkling ability and half-life. In addition, the interfacial tension can be reduced by CY-I system, which is beneficial to flooding.

### Table 4: Combination property of foam for anti-gas channeling

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Mineralization (10$^4$mg/l)</th>
<th>Ca$^{2+}$+Mg$^{2+}$ (10$^4$mg/l)</th>
<th>Surface tension (mN/m)</th>
<th>Interfacial tension (mN/m)</th>
<th>Sparkling volume (ml)</th>
<th>Half-life period (min)</th>
<th>Way of Ross-Miless</th>
<th>Way of CO$_2$ filled</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>16 (Production water)</td>
<td>4300</td>
<td>28.3</td>
<td>0.31</td>
<td>430</td>
<td>260</td>
<td>84</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25 (Simulation brine)</td>
<td>5000</td>
<td>30.6</td>
<td>0.43</td>
<td>420</td>
<td>240</td>
<td>70</td>
<td></td>
</tr>
</tbody>
</table>

In order to visually observe the foaming properties of foam in porous media, a visualization plugging model was designed as shown in Figure 7.

Evaluation of the Blocking Performance of CO$_2$ Foam

In order to visually observe the foaming properties of foam in porous media, a visualization plugging model was designed as shown in Figure 7.
Figure 7: Diagram of visualization sealing experiment process

According to the results of the visualization experiment in Figure 8, the foam in porous media can be a good system, and the flooding pressure is significantly increased.

Figure 8: Results of visualization in foam flooding experiment; status of CO\(_2\) foam (a) at the front of core and (b) at the end of core

Evaluation of the Performance of Foam Plugging

From the pressure curves of core foam flooding curves as shown in Figure 9, it can be concluded that, after the foaming agent solution is injected into cores, the injection pressure of CO\(_2\) shows an obvious increase, which indicates that the foam in cores has a good resistance to flow and a good sealing effect [5].

Field Application and Effect Assessment

History of Pu1-1 Group

According to the production status and wellbore conditions of the lower part of Es1 reservoirs in Pucheng oilfield of Zhongyuan oilfield, a pilot test of CO\(_2\) flooding was carried out on Pu 1-1 well group. The Pu 1-1 well group contained four production wells named Pu 1-349, Pu 1-368, Pu 1-67, and Pu 1-21 and one injection well named Pu 1-1. The production horizon was S1x12+3. The target group was produced by water alternating CO\(_2\) injection, which had six CO\(_2\) slugs. The gas injection rate was 40 t/d, and the water injection was 260 m\(^3\)/d. The cumulative injection volume of CO\(_2\) was 19200 t, which was equivalent to 0.25 PV.

Figure 9: Changes of pressure in different flooding method

Analysis of Field Application

Water flooding tests show that the water cut has significantly declined during the CO\(_2\)/water alternative flooding from 99.6% to 90%. However, the oil production rate has increased from 0.6 t/d to 15.9 t/d. Therefore, the predict recovery had an increase of 8.3%.

From the analysis of well flow material component, after CO\(_2\) flooding, the oil color changed from black to brown, and the viscosity decreased from 24.66 mPa.s to 7.99 mPa.s. In addition, the density of oil decreased from 0.8639 g/cm\(^3\) to 0.8353 g/cm\(^3\). The components of associated gas were similar with the original...
Research on CO₂ Flooding for Improved Oil Recovery …

hydrocarbon gas. However, the components of oil underwent a large change; the medium hydrocarbon component content increased while the heavy hydrocarbon content significantly decreased.

Moreover, the analysis of production water samples from Pu 1-67 well and Pu 6-21 well shows that the content of Ca²⁺ and Mg²⁺ ion has increased, but the pH value shows a downward trend.

Composite anti-corrosive techniques were introduced to protect the production wells. The fracture of production wells contained four tail pipes with cathodic protection as shown in Figure 10, solid anti-corrosion, sucker rods with both sides coupling, anti-corrosion pipes installed every 5-10 sucker rods, and some carbon dioxide-specific corrosion inhibitor mixed at the endpoint of production wells. The dosage of corrosion inhibitor was as follows: the concentration of dosage was 100-200 ppm before the CO₂ output, and the dosage increased to 400-600 ppm after the CO₂ output.

During the process of CO₂ pilot injection in Pu 1-1, the CO₂ concentration in production wells increased from 1.73% to 17.72% after the injection of 71t CO₂, resulting in a significant gas channeling. However, the CO₂ concentrations in production wells were recovered to the original value through the method of deep profile and foam system. Moreover, the CO₂ production was delayed for 7 months.

After the sealing channeling measurement, the volume of injected gas was expanded effectively, and the oil production rate rose from 0.3 t/day to 10.4 t/day.

CONCLUSIONS

The pressure of the lower part of Es1 reservoirs in Pucheng oilfield (20.02 MPa) was higher than the MMP of 18.42 MPa, which caused miscible flooding. The long term and high frequency of water flooding in water flooding abandoned reservoirs have generated the high permeability zone. However, water alternating CO₂ flooding could improve the swept volume effectively and control the gas breakthrough.

Based on the conditions of high temperature, high mineralization, and high CO₂ concentration, the combination of the corrosion inhibitor and sacrificial anode materials could effectively improve the problems of CO₂ corrosion. Finally, the application of water alternating CO₂ flooding, matching with deep profile control and foam system, could efficiently prevent gas channeling.

ACKNOWLEDGEMENTS

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