RESEARCH ON CO_2 FLOODING FOR IMPROVED OIL RECOVERY IN WATER FLOODING ABANDONED RESERVOIRS

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ABSTRACT

CO_2 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 CO_2 flooding, the reservoir could achieve miscible flooding. Long core displacement experiments proved that water alternating CO_2 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 CO_2 was 19219.95 ton, 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 CO_2 Injection, CO_2 Corrosion, CO_2 Foam

INTRODUCTION

CO_2 flooding has the advantage of low 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 CO_2 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 CO_2 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.

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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 CO_2 flooding was introduced in this reservoir in 2008.

RESULTS AND DISCUSSION

Experimental Results of CO_2 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/cm^3, and the viscosity of oil is 1.987 mPa.s. The gas-oil ratio is 64.3 m^3/m^3.

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 CO_2 flooding can form miscible flooding.

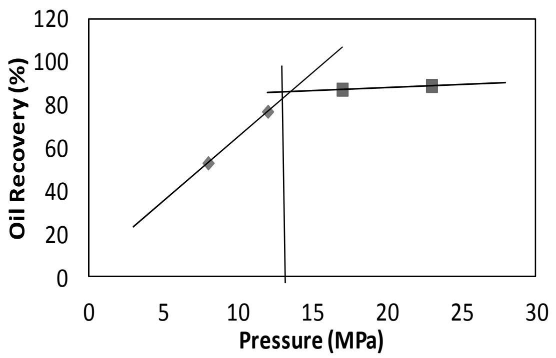

Figure 1: Slim tube experiments result of oil recovery at different pressures

Research on Injection Mode

The core used in laboratory was selected by the nature core of the lower part of Es1 reservoirs in Pucheng oilfield. The length of core is 197.4 cm and the diameter is 2.5 cm. The pore volume of core is 252.4 cm^3, and the average permeability is 245.5×10^{-3} μm^2. The irreducible water saturation was 21.23%. The property of water and oil used in laboratory was similar to the conditions of the lower part of Es1 reservoirs. The temperature was set at 82.5 °C, and back pressure was 20.2 MPa in laboratory.

In Test-1, water flooding was first conducted up to 98% of water cut, and the recovery reached 57.6%. CO_2 flooding was followed with 0.4 pore volume (PV), and the final recovery was 88.51%, as shown in Figure 2.

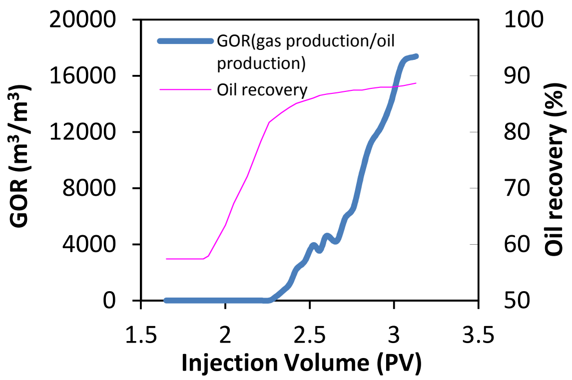

Figure 2: Curves of oil recovery and GOR (gas production/oil production) during CO_2 flooding

In Test-2, water flooding was first conducted up to 98% of water cut, and the recovery reached 57.6%. Water alternating CO_2 flooding was followed. The volume of CO_2 achieved 0.4 PV and the final recovery was 93%, as shown in Figure 3. The experiments show that the water alternating CO_2 flooding could delay the gas channeling. Therefore, water alternating CO_2 flooding after water flooding was the optimal injection to obtain a higher recovery.

Experimental Results of Water Alternating CO_2 Flooding

Experimental conditions were as above the design of the water alternating CO_2 flooding into the long-core flooding tests contained 7 slugs of CO_2, and the total injected volume was 0.15 HPV. After water driving (water cut was greater than 98%), the cumulative injection volume of CO_2 was 0.15 PV (7 cycles, each slug was 0.02 PV).

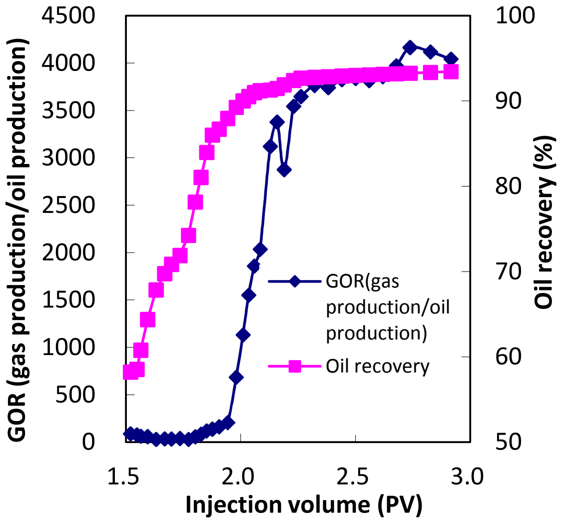

Figure 3: Curves of oil recovery and GOR (gas production/oil production) during water alternation CO_2 flooding

As shown in Figure 4, after water alternating 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 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 CO_2 corrosion.

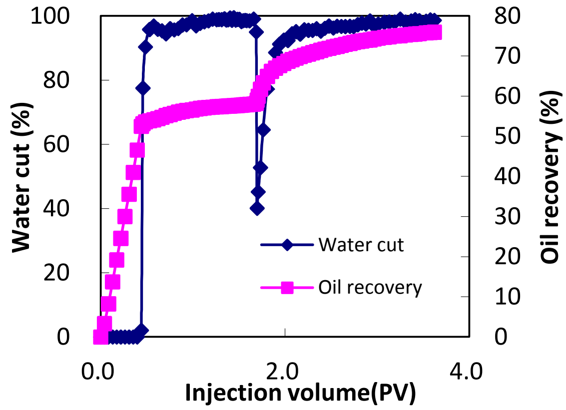

Figure 4: Curves of oil recovery and water cut during water alternation CO_2 injection

Optimization of Corrosion Inhibitor

Static immersion tests experiments were introduced by water from the production wells. Before the experiments, 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 CO_2 corrosion inhibitor and had a good inhibition effect; the concentrations used are listed in Table 1 and Figure 5.

Table 1: Optimization result of corrosion inhibitors

Concentration (mg/l)	Weight before test (g)	Weight after test (g)	Total weight loss (g)	Average weight loss (g)	Average rate of corrosion (mm/a)	Rate of corrosion inhibition (%)
0	11.0162	10.914	0.1022	0.1030	0.7378	--
	10.8771	10.7732	0.1039			
200	10.9686	10.9247	0.0439	0.0436	0.214558	70.9
	10.9973	10.9539	0.0434			
500	10.9756	10.9655	0.0101	0.0096	0.0476	93.5
	11.0189	11.0095	0.0094			

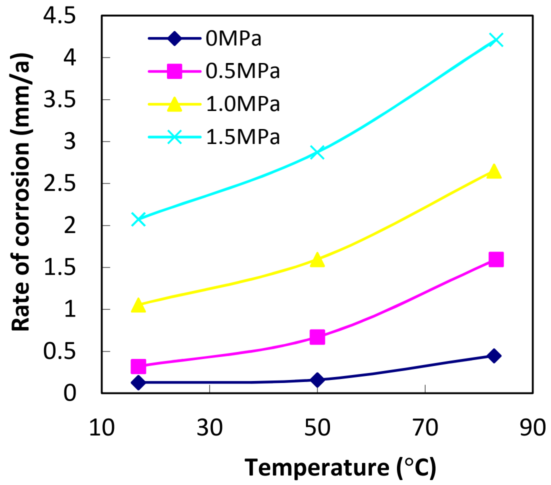

Figure 5: Rate of corrosion at different temperatures and pressures

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 Zhong-yuan 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.

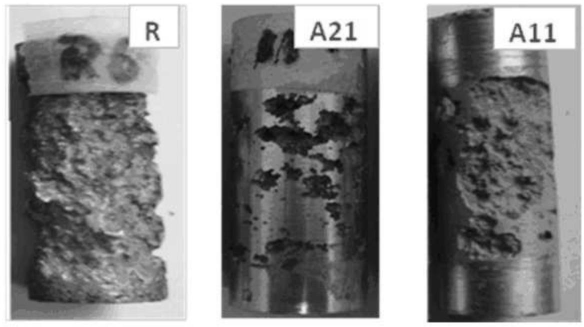

Figure 6: The dissolved states of different anode materials

Research on Deep Profile and Anti-CO_2 Channeling

The lower part of Es1 pilot experiment area is a high permeability reservoir, which has main-tained a relatively high oil 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 2: Evaluation results of the anode electrochemical performance at 80 °C

Number	Open Circuit Potential (V,vs.SCE)	Working potential (V,vs.SCE)		Specific consumption (kg/A·a)	Actual capacitance (A·h/kg)	Current efficiency (%)
		Range	Average value			
A11	-1.014	-0.946 to -1.006	-0.980	3.2505	1240.425	42.74
A21	-1.008	-0.903 to -0.978	-0.958	1.8515	1633.27	57.27
R6	-1.019	-0.833 to -0.984	-0.929	6.658	760.08	26.04

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

	1# sand-pack	2# sand-pack	3# sand-pack
Breakthrough pressure (MPa)	1.3	0.9	0.65
Recovery after plugging (%)	87.25	82.59	85.6
Incremental recovery (%)	12.5	7.01	9.36
Ratio of plugging (%)	90.3	87.7	73

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.

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.

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

Temperature (°C)	Mineralization (10^4mg/l)	Ca^{2+}+Mg^{2+} (10^4mg/l)	Surface tension (mN/m)	Interfacial tension (mN/m)	Sparkling volume (ml)	Half-life period (min)	
						Way of Ross-Miless	Way of CO_2 filled
90	16 (Production water)	4300	28.3	0.31	430	260	84
	25 (Simulation brine)	5000	30.6	0.43	420	240	70

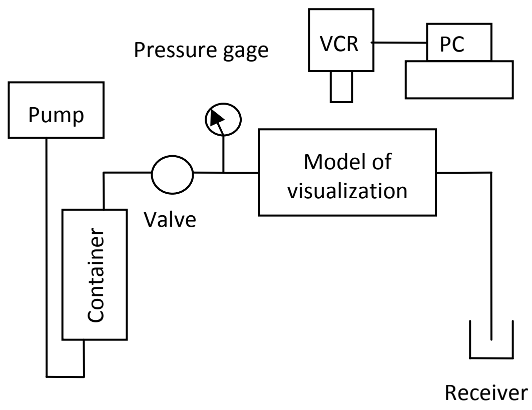

Figure 7: Diagram of visualization sealing experiment process

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.

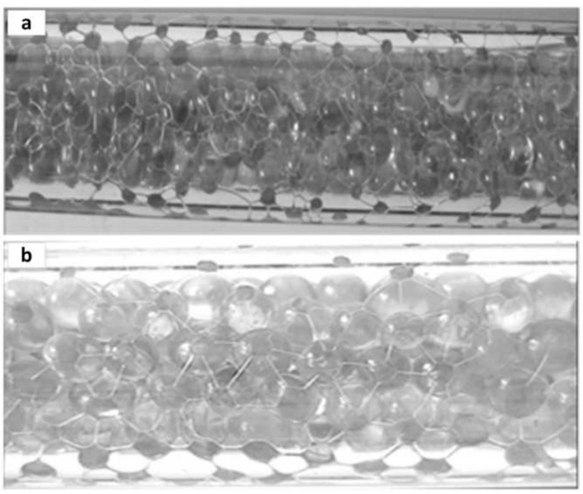

Figure 8: Results of visualization in foam flooding experiment; status of CO_2 foam (a) at the front of core and (b) at the end of core

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 cumulitive injection volume of CO_2 was 19200 t, which was equivalent to 0.25 PV.

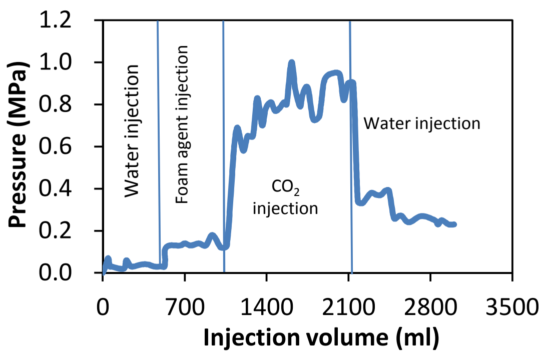

Figure 9: Changes of pressure in different flooding method

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

Moreover, the analysis of production water samples from Pu 1-67 well and Pu 6-21 well shows that the content of Ca^{2+} and Mg^{2+} 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 CO_2 output, and the dosage increased to 400-600 ppm after the CO_2 output.

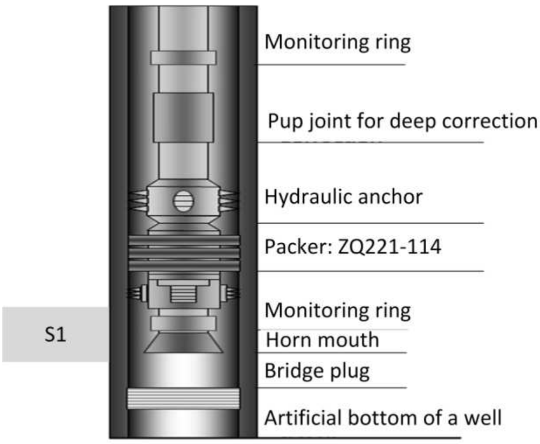

Figure 10: A schematic diagram of tube structure in production well

Under the implementation of composite anti-corrosion technology, through the monitoring of hanging ring in production wells for 333 days, the inner corrosion rate was 0.0045 mm/a, and the outer ring of corrosion rate was 0.0152 mm/a, which was below the standards of Sinopec.

During the process of CO_2 pilot injection in Pu 1-1, the CO_2 concentration in production wells increased from 1.73% to 17.72% after the injection of 71t CO_2, resulting in a significant gas channeling. However, the CO_2 concentrations in production wells were recovered to the original value through the method of deep profile and foam system. Moreover, the CO_2 production was delayed for 7 months.

After the sealing channeling measurement, the volume of injected gas was expanded effect-tively, 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 CO_2 flooding could improve the swept volume effectively and control the gas breakthrough.

Based on the conditions of high temperature, high mineralization, and high CO_2 concentration, the combination of the corrosion inhibitor and sacrificial anode materials could effectively improve the problems of CO_2 corrosion. Finally, the application of water alternating CO_2 flooding, matching with deep profile control and foam system, could efficiently prevent gas channeling.

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