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Experimental Study of CCS Application in Late Water-Driven Reservoirs

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ABSTRACT

Under the background of “double carbon” target, injection of CO_2 into oil reservoirs has attracted a lot of attention as a key technology pathway to enhance crude oil recovery and realize geological storage of CO_2. In the past decade, CCUS (Carbon Capture, Utilization and Storage) technology has become a research hotspot in the process of global energy transition by virtue of its dual benefits of carbon reduction and production increase in the oil and gas industry. Currently, most of the major oilfields in China have been under water-driven development for a long period of time, and they are facing the problem of high and stable production, and their development programs need to be adjusted urgently. Based on the above situation, this study carried out indoor oil drive physical simulation experiments, aiming to compare the effect of CO_2 oil drive after water drive. The experimental results show that CO_2-assisted oil drive is effective, the recovery rate from the test basis and technical reference, is expected to help the oilfield to meet the energy demand at the same time, and effectively promote the realization of the “double carbon” goal.

KEYWORDS

CO_2 drive; CCUS technology; Recovery; Physical simulation experiments.

1. INTRODUCTION

Driven by the acceleration of global energy transition and the strategic goals of "dual carbon" (carbon peak and carbon neutrality), how to ensure energy security while achieving greenhouse gas emissions reduction has become a major challenge for the oil and gas industry. The technical pathway of injecting CO_2 into oil reservoirs for enhanced oil recovery (EOR) and simultaneous geological storage of CO_2, due to its dual benefits of "carbon reduction - production increase", has become one of the core technologies to promote the green and low-carbon development of the energy industry [1-3]. In recent decade, the large-scale application of CCUS (Carbon Capture, Utilization and Storage) technology in the oil and gas sector has advanced rapidly. More than 150 CO_2 flooding projects have been deployed globally, with a cumulative CO_2 storage exceeding 1 billion tons [4]. This technology can not only improve the degree of crude oil recovery by enhancing the seepage characteristics of oil reservoirs, but also permanently store industrial-emitted CO_2 underground, helping to resolve the contradiction between energy production and carbon emissions. Therefore, it has become a research hotspot of common concern in academia and industry[5-6].

As one of the world's largest crude oil producers and consumers, China's main oilfields have generally undergone decades of waterflood development and face severe challenges of "high water cut, high recovery degree, and low reserve-production ratio" In eastern old oilfields represented by Daqing Oilfield and Shengli Oilfield, the average comprehensive water cut has exceeded 85%. Inefficient and ineffective water injection cycles have caused formation energy imbalance and complicated remaining oil distribution, leading to a year-by-year decline in the effectiveness of traditional waterflood development. Against this backdrop, CO_2 flooding technology, with its unique advantages (such as low interfacial tension, easy solubility in crude oil, and improved mobility ratio), is regarded as a key means to tap potential and enhance efficiency in old oilfields. This paper aims to reveal the changes in remaining oil distribution and the impact on subsequent waterflooding after CO_2 injection into the formation through laboratory physical simulation experiments, providing theoretical support for field scheme design [7].

2. EXPERIMENTAL PROCEDURE

Through the use of sand-packed tubes, a physical model was established to simulate the distribution of abundant remaining oil in the high structural parts of the reservoir for indoor gas-assisted oil displacement experiments. The objectives were to clarify the oil displacement efficiency of two gas-assisted oil displacement methods and evaluate their impacts on remaining oil distribution and oil displacement effectiveness.

The experiment utilized sand-packed tubes with dimensions of ø3.8 cm × 30 cm. The parameters of the sand-packed tubes are shown in Table 1, where Sand-Packed Tube I was used for simulation experiments, and Sand-Packed Tubes II/III were used for remaining oil analysis.

Table 1. Sand-Packed Tube Parameters

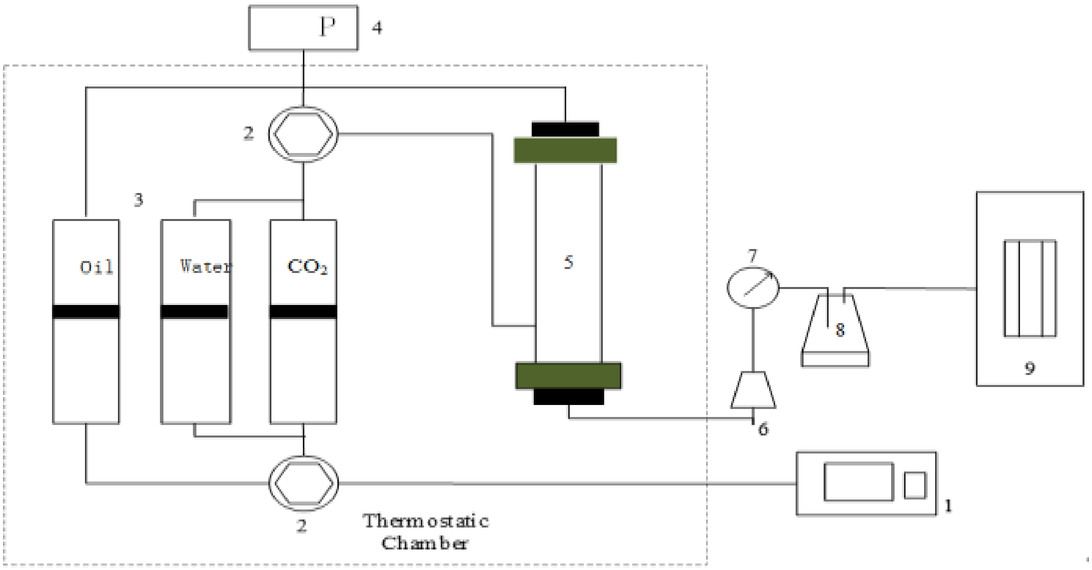
Sand-packed tube	Saturated water volume /mL	Saturated oil volume /mL	Gas permeability /mD	Porosity /%	Oil saturation /%
I	120	90	427	35.29	75.00
II	128	91	620	37.65	72.22
III	121	88	530	35.59	73.77

2.1. Experimental Steps

(1) Waterflood Production Phase: This phase involves waterflood production under current formation pressure conditions (10 MPa). The injection point is selected at 1/3 of the distance from the lower end to create conditions where the oil saturation is higher in the upper part of the reservoir and lower in the lower part below the injection end after waterflooding.

(2) Gas Huff and Puff Phase: After the waterflood ends, the outlet end is closed, and a certain amount of gas is injected followed by a shut-in period (well soaking). Production is resumed after the shut-in period.

(3) Subsequent Waterflood Phase: Following the gas huff and puff phase, waterflood production is conducted again. The experimental flow chart is shown in Fig. 1, and the displacement model device is shown in Fig. 2.



1 ISCO Constant Speed and Pressure Pump 2 Six-Way Valve 3 Intermediate Vessel 4 HB-1 Pressure Monitoring System 5 Sand-Packed Tube 6 Backpressure Valve 7 Pressure Gauge 8 Oil-Gas Separator 9 Gas Meter

Figure 1. Displacement Experiment Flow Chart

Figure 2. Displacement Device Model

The specific experimental methods for gas-assisted oil displacement are as follows:

(1) Waterflood Displacement Experiment
Set the backpressure valve pressure to formation pressure (10 MPa), and conduct pressure-maintained waterflood displacement at a rate of 0.1 mL/min. Stop the displacement when no oil is produced at the outlet.

(2) CO_2-Assisted Oil Displacement Experiment
After the waterflood displacement experiment, start the CO_2-assisted oil displacement experiment. Set the pressure to 10 MPa and the soaking time to 48 hours. The specific experimental steps are as follows:

1) Close the outlet valve after the waterflood ends;

2) Inject CO_2 gas from the inlet end. After a cumulative injection of 0.2 PV, close the inlet valve;

3) After soaking for 48 hours, open the outlet valve and record changes in pressure and recovery rate;

4) After the CO_2 huff and puff ends, maintain the current formation pressure (10 MPa) and conduct pressure-maintained waterflood displacement at a water injection rate of 0.1 mL/min;

5) Stop the waterflood when no oil is produced, and record the injected PV volume, recovery rate, and water cut.

3. EXPERIMENTAL RESULTS

3.1. Waterflood Experiment

The results of the waterflood experiment are shown in Table 2 and Fig. 3:

Table 2. Waterflood Experiment Results

Water injection volume /PV	Cumulative oil production /mL	Cumulative water production /mL	Water cut /%	Recovery rate /%
0.00	0.00	0.00	0.00	0.00
0.10	11.50	onset of water production	0.00	12.78
0.18	14.80	1.40	29.79	16.44
0.23	17.25	5.60	63.16	19.17
0.30	20.25	12.00	68.09	22.50
0.35	21.00	15.00	80.00	23.33
0.43	22.25	34.38	93.94	24.72
0.48	22.75	37.50	86.21	25.28
0.63	23.00	53.00	98.41	25.56

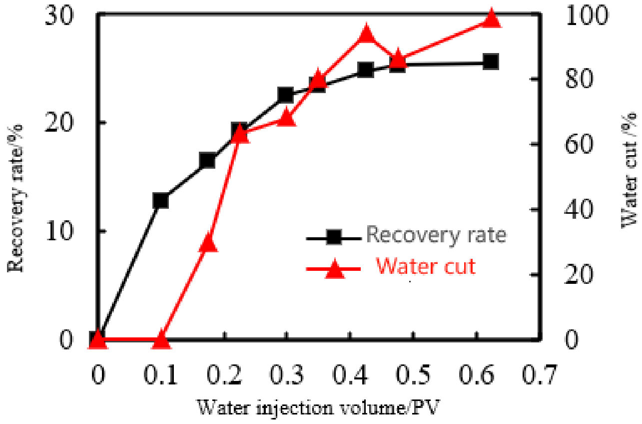


Figure 3. Results of Water - flooding Experiment

According to Table 2 and Figure 3, the results of water - flooding are as follows: when the water injection volume is 0.1PV, the oil production is 11.5mL, and the outlet end starts to produce water, with the water - free recovery rate being 12.78%; when the water injection volume is higher than 0.63PV, it no longer produces oil. At this time, the water cut is 98.41%, and the ultimate water - flooding recovery degree is 25.56%.

3.2. CO_2 - Assisted Oil Displacement Experiment

Table 3. Results of Subsequent Water-Flooding

Water injection volume /PV	Cumulative oil production /mL	Cumulative water production /mL	Water cut /%	Recovery rate /%
0.00	0.00	0.00	0.00	25.56
0.11	4.20	15.75	78.95	30.22
0.23	4.80	25.65	94.29	30.89
0.34	6.25	34.20	85.50	32.50
0.45	6.75	45.45	95.74	33.06
0.56	7.75	59.15	93.20	34.17
0.68	8.25	72.00	96.25	34.72
0.80	8.60	88.50	97.92	35.11

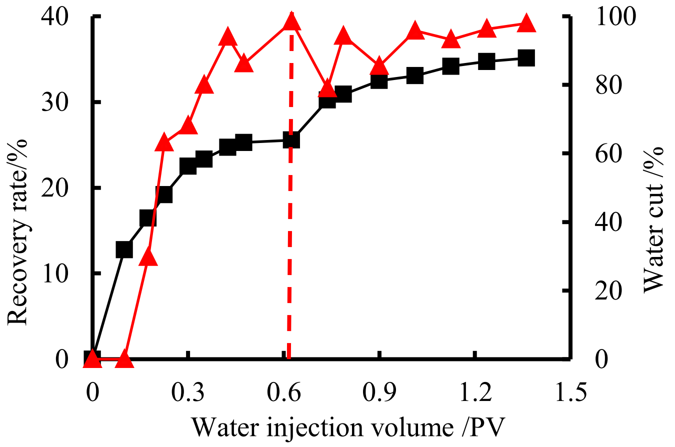


Figure 4. Results of Subsequent Water-Flooding Experiment

According to Table 4 and Figure 4, when water injection reached 0.63 PV with a water cut of 98.41% during waterflooding, CO_2 injection and soaking were conducted. After the soaking period, subsequent waterflooding experiments were carried out. The subsequent waterflooding involved a cumulative water injection of 0.8 PV, cumulatively increasing the recovery rate by 9.85%. Specifically, when the cumulative injected PV reached 0.11 PV, the water cut was 78.95%. As the cumulative injected PV increased to 0.23 PV, the water cut rapidly rose to 94.29%. Oil production ceased when the water injection reached 0.8 PV, and the ultimate recovery rate reached 35.11%. These results demonstrate that the CO_2-assisted displacement method can reduce water cut and enhance oil recovery.

4. REMAINING OIL ANALYSIS

To clarify the changes in the internal remaining oil distribution within porous media after CO_2 and N_2-assisted oil displacement, analyses were conducted on the remaining oil distribution at different positions in the sand-packed tube at different stages. The remaining oil distributions after water flooding, CO_2-assisted oil displacement, and CO_2+N_2-assisted oil displacement were compared to evaluate the influence of gas-assisted oil displacement on remaining oil distribution changes and the impact of remaining oil distribution alterations on oil displacement efficiency.

(1) Experimental Setup and Materials

1) Experimental Materials:

Oil sand obtained from the sand-packed tube after gas-assisted oil displacement.

2) Experimental Equipment:

Thermostatic chamber, muffle furnace, crucible.

a. Oil sand within the sand-packed tube

b. Muffle furnace c. Crucible

Figure 5. Experimental Setup and Materials

(2) Experimental Protocol

The sand within the sand-packed tube was removed, and oil sand samples were collected from different sections. The samples were dried and calcined to determine the remaining oil content and water content in different parts of the sand-packed tube, which were used to analyze the remaining oil distribution in different sections of the porous media.

(3) Experimental Results

a. sampling b. after drying c. after calcination

Figure 6. Comparison of Oil Sand at Different Stages

Table 4. Remaining Oil Distribution after Gas-Assisted Oil Displacement

Position of the Sand-Packed Tube		1/4	2/4	3/4	4/4
After water flooding	Sampling /g	21.425	25.317	24.539	22.927
	Water content /mL	0.285	0.263	0.255	0.295
	oil content /mL	0.911	0.643	0.468	0.093
	oil saturation /%	76.144	70.969	64.744	24.056
After CO_2-assisted water flooding	Sampling /g	23.155	26.778	23.841	20.565
	Water content /mL	0.283	0.260	0.269	0.296
	oil content /mL	0.752	0.365	0.279	0.064
	oil saturation /%	72.656	58.388	50.888	17.831

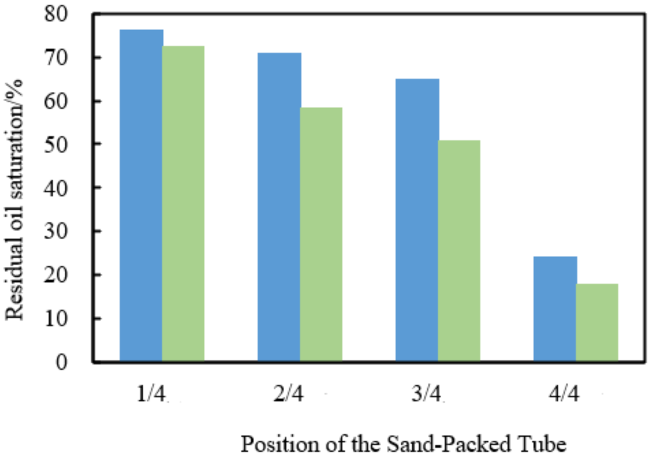


Figure 7. Remaining Oil Distribution after Gas-Assisted Oil Displacement

Through analysis, it is found that the residual oil distribution in porous media undergoes the following changes after CO_2-assisted oil displacement:

1) The residual oil proportion at the top 1/4 section decreases from 76.144% to 72.656%, with a reduction of 3.488%;

2) The residual oil proportion at the 2/4 section decreases from 70.969% to 58.388%, with a reduction of 12.581%;

3) The residual oil proportion at the 3/4 section decreases from 64.744% to 50.888%, with a reduction of 13.856%;

4) The residual oil proportion at the 4/4 section decreases from 24.056% to 17.831%, with a reduction of 6.225%.

Compared with water flooding, CO_2-assisted oil displacement can effectively displace residual oil in the high structural parts of the reservoir. This is possibly due to the fact that after gas injection, CO_2 rapidly diffuses upward and enters small pore channels that water cannot penetrate, displacing part of the crude oil dissolved with CO_2.

5. CONCLUSIONS

(1) After CO_2 huff and puff, subsequent water flooding experiments were conducted with a cumulative water injection of 0.8 PV in the subsequent water flooding stage, enhancing oil recovery by 9.55% compared to pure water flooding.

(2) Analysis of remaining oil distribution shows that CO_2-assisted oil displacement reduced the average oil saturation at the top of the sand-packed tube by 11.897%.

(3) CO_2 storage in late-stage water-flooded oilfields can effectively displace "attic oil", with its oil displacement process achieving dual benefits of carbon sequestration and enhanced oil recovery, thus facilitating the low-carbon application of CCUS technologies in oilfield development.

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