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Research Article

Sensitivity Analysis and Multiobjective Optimization of CO_2 Huff-N-Puff Process after Water Flooding in Natural Fractured Tight Oil Reservoirs

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The CO_2 huff-n-puff is an effective substitute technology to further improve oil recovery of natural fractured tight oil reservoirs after water flooding, for its high displacement efficiency and superior injectivity. The CO_2 huff-n-puff process is influenced by many factors, such as miscible degree, complex fracture networks, and production schemes. What is worse, those influence facts affect each other making the process more complex. Many researchers concentrated on mechanisms and single sensitivity analysis of CO_2 huff-n-puff process, whereas few optimized this process with the consideration of all influence factors and multiobjective to get favorable performance. We built multiobjective consisted of miscible degree, oil recovery, and gas replacing oil rate considering the aspects of CO_2 flooding special characteristic, technical effectiveness, and economic feasibility, respectively. We have taken Yuan 284 tight oil block as a case, firstly investigated sensitivity analysis, and then optimized CO_2 huff-n-puff process using orthogonal experiment design with multifactors and multiobjectives. The optimization results show CO_2 huff-n-puff can significantly improve oil recovery by 8.87% original oil in place (OOIP) compared with water flooding, which offers guidelines for field operations.

1. Introduction

For tight oil reservoirs with natural fractures, the development performance varies due to the influence of natural fractures. Water flooding becomes feasible for natural fractures to provide a high permeability flow path [1]. However, the nature fracture also brings adverse effects at later development stage. The injected water flows along natural fractures and breaks through early, reducing the sweep efficiency of water flooding severely. The more injected water becomes invalid, and the more oil in matrix is left without effective recovery. Vertical wells were used instead of multiple fractured horizontal wells (MFHWs), because once MFHWs suffer water breakthrough, it is hard to conduct water plugging [2].

To further improve oil recovery after water flooding, CO_2 huff-n-puff is proposed. This is because CO_2 huff-n-puff can take the advantages of natural fractures and avoid their bad effects. CO_2 huff-n-puff fully uses the enormous areas provided by nature fractures to get contact with oil, and only extracts oil around injection wells unlike CO_2 continuous flooding suffers gas breakthrough [3]. The studied Yuan 284 block is rich in natural fractures [4, 5]; based on these aforementioned facts, CO_2 huff-n-puff is proposed as a substitute technology after water flooding to further improve oil recovery.

The oil recovery of CO_2 huff-n-pull is affected by many factors; what is worse, multifactors affect each other making the process more complex. Both good and bad results were obtained on site, and the process optimization has become

an imperative issue needed to be settled. Many researchers have investigated the mechanisms and single sensitivity analysis of CO_2 huff-n-puff process in the literature.

Fracture density and fracture geometry influence huff-n-puff performance significantly, because fractures provide CO_2 with high conductive flow paths and enormous contact areas with oil [6–8]. Fractures also impair CO_2 and oil miscible degree by influencing pressure maintenance [9, 10]. Miscible degree promotes oil recovery by improving displacement efficiency, so injection pressure higher than minimum miscible pressure (MMP) is needed [11]. CO_2 molecular diffusion plays an important role in enhancing oil recovery during CO_2 soaking time and promotes the mixture of CO_2 with matric oil swelling oil volume and reducing oil viscosity [9]. CO_2 molecular diffusion needs enough soaking time to fully act its role, but soaking time is not the longer the better, and there is an optimal point [12, 13]. The reopen production bottom hole pressure affects oil recovery significantly by influencing drive mechanisms. It was found that CO_2 solution drive due to low bottom hole pressure plays a more important role than CO_2 miscible driver with high bottom hole pressure [14]. Other researchers also investigated the interaction of multifactors and found that primary depletion time, CO_2 injection time, and reopen production time have obvious influence on each other [15].

Unfortunately, few optimized the CO_2 huff-n-puff process considering multiple factors effects and the interactions between them. In this research, Yuan 284 block of Changqing oil field was taken as a case, and firstly single factor sensitivity analysis was conducted to investigate the influence rule on huff-n-puff performance. Then, multiobjective goal consisted of miscible degree, oil recovery, and gas replacing oil rate was built. It fully considered CO_2 flooding special characteristic, technical effectiveness, and economic feasibility. Orthogonal experimental design is a widely used multifactor optimal method, for it can select the optimal project without calculating all possible schemes, reducing the calculated scheme number and computational cost [16, 17]. Based on the orthogonal experimental design method, the CO_2 huff-n-puff process with multifactors influence and multiobjective goal was optimized, which provides guidelines for treatments on site.

2. Reservoir Model Description

In this section, the pilot test reservoir model of Yuan 284 block was described, including geometry model, fluid model, relative permeability curve, and history match. It provided the basic simulation model for further sensitivity analysis and multiobjective optimization.

The average permeability and porosity of Yuan 284 block are 0.41 mD and 11.08%, and it belongs to tight oil reservoirs. The target reservoir bury depth is 2100 m, and reservoir temperature and initial pressure are 70.6°C and 15.1 MPa. The target reservoir has four well groups, and they are all inverted nine-point diamond-shaped patterns. The bubble map of production rates and water injection rates in August 2012 were shown in Figure 1. It indicates that
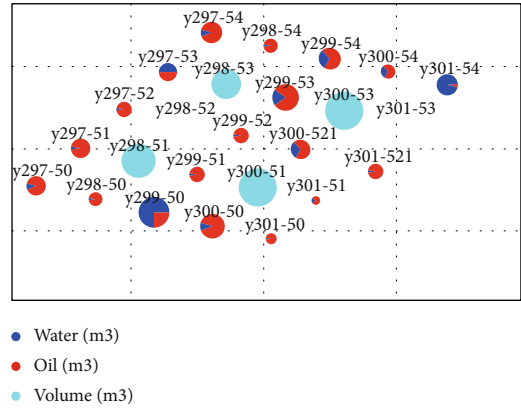

Figure 1: Bubble map of production and injection rates in August 2012.

the reservoir has serious heterogeneity for water cut of several wells are extremely higher than the others. The CO_2 huff-n-pull was proposed to further improve oil recovery. The water injection well in the center of each well group as before and the other production wells as CO_2 huff-n-pull wells are considering reservoir pressure maintenance and remaining oil distribution.

For this target reservoir with natural fractures, the simulation of natural fractures is very important, and we used high permeability channels to mimic natural fractures. The high permeability channels were determined by history match, that is, we modified the high permeability channels until the history data and calculated data achieve good match, and their distributions before and after history match are different as shown in Figure 2. The oil and water production total achieved good match with the real data after history match as shown in Figure 3, because natural fractures were appropriately simulated by changed high permeability channels.

We used the compositional fluid model to describe the complex interaction of CO_2 and crude oil. To improve computational efficiency, we grouped all compositions of CO_2 and oil fluid system into 9 pseudocomponents in Table 1, according to the composition's properties and expert experience. We used RP3-EOS to describe the phase behavior of CO_2 and oil system, and the parameters of EOS were determined for further fluid simulation. We turned and determined the RP3-EOS parameters by fitting the simulation results and experimental results. The determined EOS parameters were shown in Table 1. What is more, the MMP was also determined by slim-tube experiment, when the pressure is higher than the MMP 16.8 MPa, the miscible condition is achieved and the process gets a favorable displacement efficiency.

Relative permeability curves accounting for dynamic interaction of reservoir fluids and rock media were measured by core flooding experiments according to Darcy's law as Figure 4 shows. The residual oil saturation of water flooding is 0.31, and the ideal displacement efficiency of water flooding is only 44.7% OOIP, which is far below CO_2 flooding displacement efficiency, and this is the main reason why CO_2 flooding is proposed as the substantial EOR technology after water flooding.
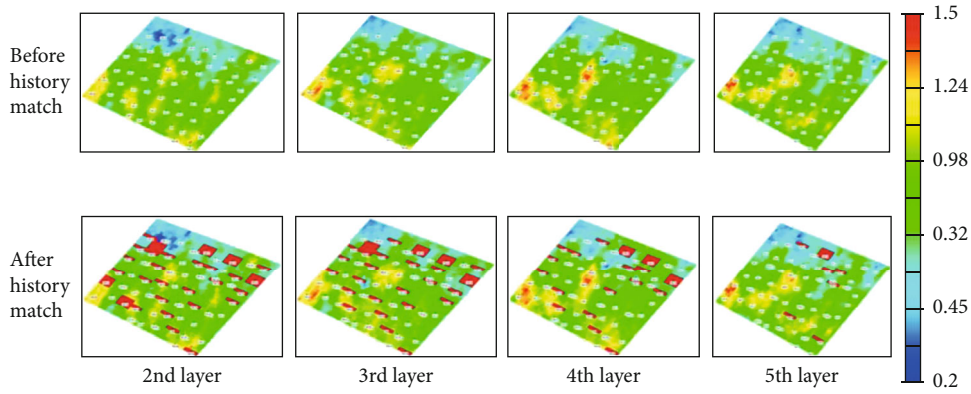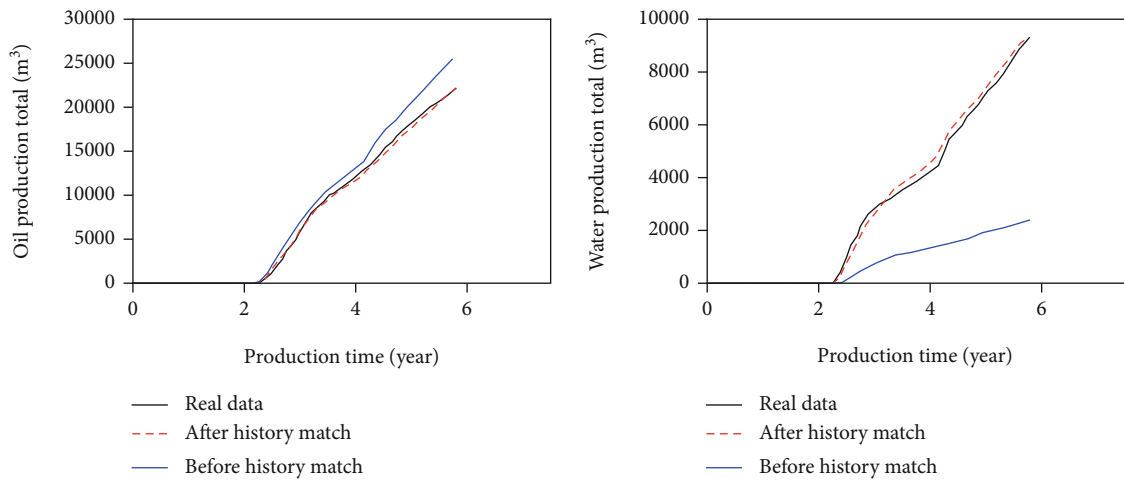
FIGURE 2: Permeability distribution before and after history match.

(a) Oil production total before and after history match

(b) Water production total before and after history match

FIGURE 3: Oil and water production total before and after history match.

TABLE 1: Pseudocomponents and EOS parameters.

Component	mol (%)	Critical pressure (MP)	Critical temperature (K)	Omega A	Omega B	Acentric factor	Critical volume	Critical Z factor
CO_2	0.08	7.39	304.7	0.457	0.078	0.225	0.09	0.27
N2C1	27.49	4.57	188.8	0.416	0.063	0.014	0.10	0.29
C2	8.16	4.88	305.4	0.367	0.024	0.099	0.15	0.29
C3	8.53	4.19	513.3	0.657	0.064	0.155	0.20	0.20
C4	6.65	3.34	496.2	0.611	0.058	0.135	0.26	0.21
C5	4.61	1.61	291.3	0.573	0.083	0.082	0.31	0.21
C6	3.32	8.59	496.7	0.818	0.034	0.269	0.35	0.73
C7-C10	14.64	5.61	641.9	0.178	0.049	0.363	0.45	0.47
C11+	26.52	2.67	726.9	0.704	0.109	0.424	0.83	0.37

3. Sensitivity Analysis

We investigated the effects of CO_2 injection volume, injection time, soaking time, production bottom hole pressure, reopen production time, and huff-n-puff cycle number on the oil recovery. The parameters of the basic model were as follows: one cycle CO_2 huff-n-puff process consists of 10 days CO_2 injection time, 5 days soaking time and 200 days reopen production time. The one cycle CO_2 injection volume is 988.5 t, the production bottom hole pressure is

(a) Oil and water relative permeability

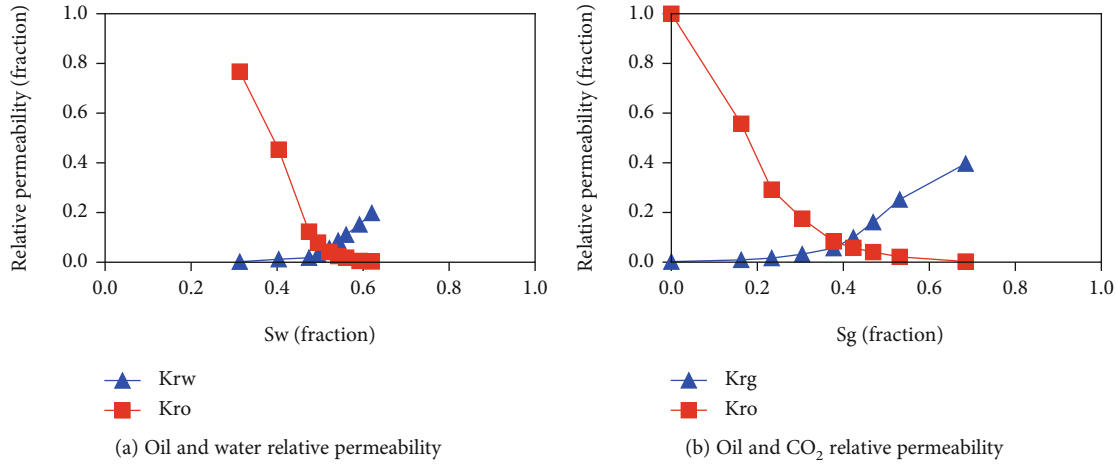(b) Oil and CO_2 relative permeability

FIGURE 4: Relative permeability curves of Yuan 284 block.

7 MPa, and the total cycle number is 5. When we studied the effect of a single factor on oil recovery, the other factors were kept the same as the basic model set.

We first investigated the effect of CO_2 injection volume on oil recovery. As Figure 5(a) shows the oil recovery increases with the increased injection volume from 197.7 t to 988.5 t, the increased CO_2 injection volume increases the amount of CO_2 dissolved in the matrix oil, and more oil swells and easily flows out for decreased viscosity. What is more, the increased CO_2 volume increases the pressure around injection wells, which improves CO_2 and oil miscible degree and displacement efficiency obviously. However, after a point, the oil recovery stops increasing from 988.5 t to 1383.9 t and even decreases with the increased injection volume from 1383.9 t to 1779.3 t, because the excessive injected CO_2 is not fully utilized and even expels the oil away from the well, which impairs the reopen production performance.

Figure 5(b) shows the oil recovery increases with the increased CO_2 injection time, indicating that slow CO_2 injection rate is favorable to oil recovery. This is because the injected CO_2 with a lower injection rate has more time to propagate forward and mix with oil, which increases the contacted oil amount and gets more favorable mixing effect.

Figure 6(a) shows the oil recovery increases with the increased soaking time, but after a point slightly decreases with the increased soaking time. This is because due to the extremely low permeability of a tight oil reservoir, CO_2 molecular diffusion needs a certain time to mix with matric oil and achieve better performance. However, too long soaking time leads to the gravity separation of CO_2 and oil in fractures, which results in the slightly decreased oil recovery.

Figure 6(b) shows the oil recovery significantly increases with the decreased bottom hole pressure. The decreased bottom hole pressure increases the potential of dissolved CO_2 releases from oil and increases the CO_2 solution driver proportion. However, it decreases CO_2 and oil miscible degree and displacement efficiency, and CO_2 miscible drive proportion decreases. It illustrates that for CO_2 huff-n-puff process, the CO_2 solution drive contributes more on oil recovery than CO_2 miscible drive.

Figure 7(a) shows the oil recovery significantly increases with the increased reopen production time from 7.75% OOIP to 14.63% OOIP. This illustrates that increasing reopen production time leads to favorable oil recovery, for it fully mines the potential of the injected CO_2 during the huff process.

Figure 7(b) shows the oil recovery increases with the increased huff-n-puff number, while the gas replacing oil rate decreases as the cycle number increases. This is because more oil around the huff-n-puff well was extracted by injected CO_2 with the increased cycle number, so the oil recovery increases. However, the oil saturation around the huff-n-puff well decreases with the increased cycle number, and the injected CO_2 efficiency decreases resulting in the decreased gas replacing oil rate.

4. Multiobjective Optimization

For CO_2 huff-n-puff process optimization, the optimization objective determination is very important. The optimization objective should comprehensively consider the aspects of CO_2 flooding special characteristic, technical effectiveness, and economic feasibility. In this research, multiobjectives consisted of miscible degree, oil recovery, and gas replacing oil rate were used to describe these aspects comprehensively. Since the miscible degree is significantly affected by pressure, the average pressure was used to describe the miscible degree for convenience. What is more, we adopted the orthogonal experimental design method to optimize the CO_2 huff-n-puff process considering multifactor influences and multiobjective goals.

In Section 3, we investigated the effect of a single factor on oil recovery. However, the optimization design process cannot be determined by sensitivity analysis, because the oil recovery is simultaneously influenced by many factors. We selected CO_2 injection volume, injection time, soaking time, production bottom hole pressure, reopen production time, and cycle number as influencing factors, and each influencing factor has 5 levels. If we use the full experimental design method, all possible schemes 7776 are needed to test for optimization, and the computational cost is very high. To avoid
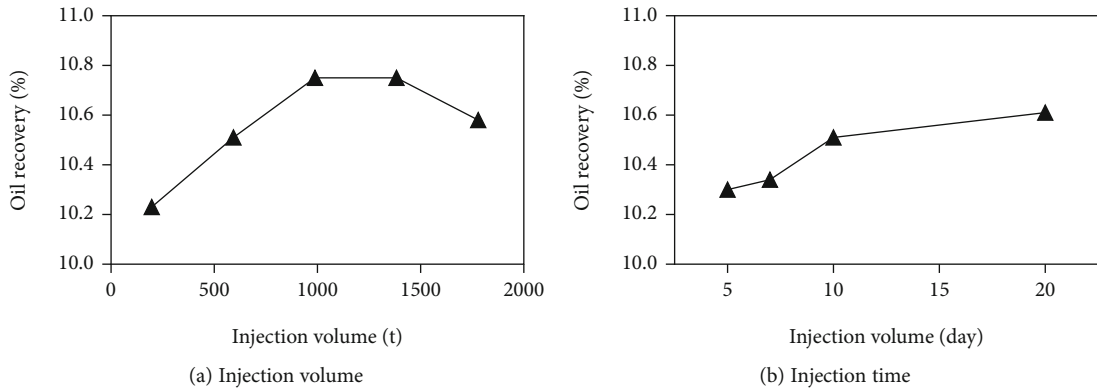
(a) Injection volume

(b) Injection time

FIGURE 5: Effects of CO_2 injection volume and injection time on oil recovery.
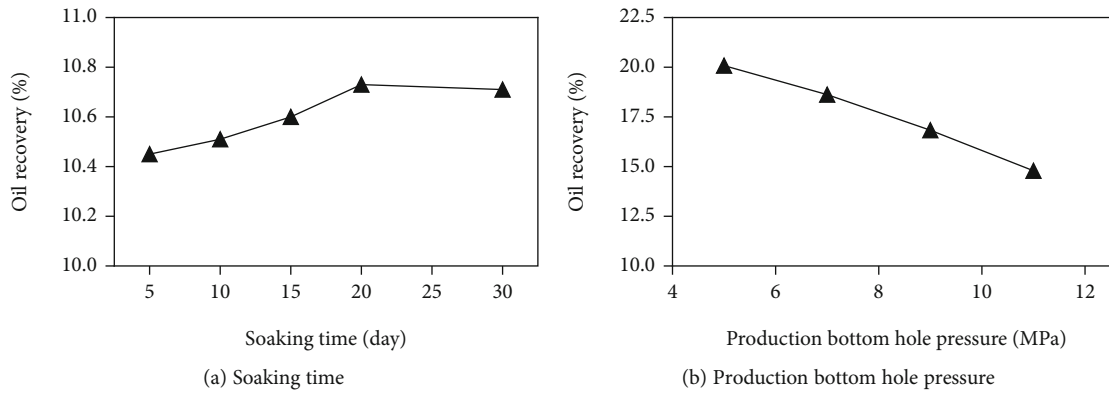

(a) Soaking time

(b) Production bottom hole pressure

FIGURE 6: Effects of soaking time and production bottom hole pressure on oil recovery.

(a) Reopen production time
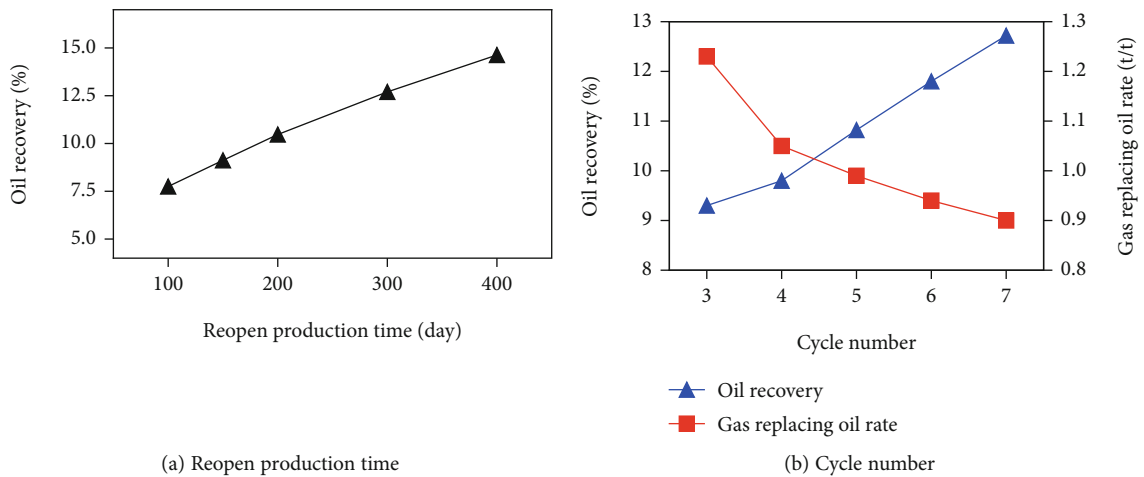

(b) Cycle number

FIGURE 7: Effects of reopen production time and cycle number on oil recovery.

this drawback, the orthogonal experimental design was proposed for it only selects certain representative samples from all possible schemes and, obviously, reduces experimental design amounts to 25 schemes. The concrete design indices and simulation results were shown in Table 2.

Multiobjective optimization designs were conducted, and the three objective indices were transformed into one comprehensive objective to facilitate evaluation. The comprehensive objective scores were calculated by formula (1). The multiplied weights were determined by expert experience

TABLE 2: Orthogonal experimental design indices and evaluation results.

No.	Multifactors						Multiobjectives			COS
	F1	F2	F3	F4	F5	F6	O1	O2	O3	
1	98.85	2	5	150	3	6	13.98	7.07	10.85	39
2	98.85	6	10	200	4	7	14.12	8.22	6.74	37
3	98.85	10	15	300	5	8	14.16	9.41	6.73	40
4	98.85	14	20	400	6	9	14.61	12.45	8.47	48
5	98.85	18	25	500	7	10	14.85	14.48	8.9	53
6	197.7	2	10	300	6	10	14.66	13.18	6.77	48
7	197.7	6	15	400	7	6	14.08	18.26	6.12	57
8	197.7	10	20	500	3	7	13.89	13.02	9.02	49
9	197.7	14	25	150	4	8	14.52	8.99	3.91	36
10	197.7	18	5	200	5	9	14.64	10.61	4.05	40
11	593.1	2	15	500	4	9	14.21	14.34	10.06	53
12	593.1	6	20	150	5	10	15.15	8.58	1.07	33
13	593.1	10	25	200	6	6	14.09	11.89	1.4	39
14	593.1	14	5	300	7	7	14.28	15.04	1.59	46
15	593.1	18	10	400	3	8	14.31	11.04	2.39	39
16	988.5	2	20	200	7	8	14.37	12.16	4.16	43
17	988.5	6	25	300	3	9	14.55	9.4	1.49	35
18	988.5	10	5	400	4	10	14.83	12.01	1.32	40
19	988.5	14	10	500	5	6	14.24	18.19	1.8	52
20	988.5	18	15	150	6	8	14.92	10.12	0.63	36
21	1383.9	2	25	400	5	7	13.8	15.24	9.53	54
22	1383.9	6	5	500	6	8	14.63	19.58	1.98	56
23	1383.9	10	10	150	7	9	15.17	10.89	0.49	37
24	1383.9	14	15	200	3	10	15.35	8.01	0.64	32
25	1383.9	18	20	300	4	6	14.19	11.96	0.9	39
A1	43.4	47.4	44.2	36.2	38.8	45.2				
A2	46.0	43.6	42.6	38.2	41.0	46.5				
A3	42.0	41.0	43.6	41.6	43.8	41.67				
A4	41.2	42.8	42.4	47.6	45.4	42.6				
A5	43.6	41.4	43.4	52.6	47.2	41.2				
R	4.8	6.4	1.8	16.4	8.4	5.3				

F1, F2, F3, F4, F5, and F6 are injection volume, t; injection time, day; soaking time, day; reopen production time, day; cycle number and bottom hole pressure, MPa, respectively. O1, O2, and O3 are average pressure, MPa; oil recovery, %; and gas replacing oil rate, t/t, respectively. COS is comprehensive objective scores; Ai is the ith index average scores; R is range of average scores.

and study goals. The comprehensive objective scores calculation results were shown in Table 2. It shows that the 7th scheme gets the maximum score of 57 and is the optimal design.

$$COS = 2 \times OR + 1 \times GRO + 1 \times P_{avg}, \tag{1}$$

where COS is the comprehensive objective scores, OR is the oil recovery, GRO is the gas replacing oil rate, and P_{avg} is the reservoir average pressure.

The range of average scores represents the influence degree of factors on target goal, and it can be concluded that the influence degree ranking of multifactors is the following: reopen production time, cycle number, injection time, bottom hole pressure, injection volume, and soaking time. The

reopen production time has the most obvious effect on the comprehensive objective. The soaking time affects oil recovery by CO_2 molecular diffusion mechanism during the well shut period, but the effect of it is the least compared with other factors during the whole production period.

The optimal scheme was determined based on these aforementioned investigations, and the optimal factor combination of Yuan 284 block is that one cycle CO_2 injection volume is 197.70 t, the CO_2 injection time is 6 days, the soaking time is 15days, the reopen production time is 400 days, the production bottom hole pressure is 6 MPa, the cycle number is 7, and the total production time is about 8 years.

The selected optimal scheme was calculated, and the average reservoir pressure and oil production rate of the CO_2 huff-n-puff process were shown in Figure 8. For the optimal CO_2 huff-n-puff process, the average reservoir
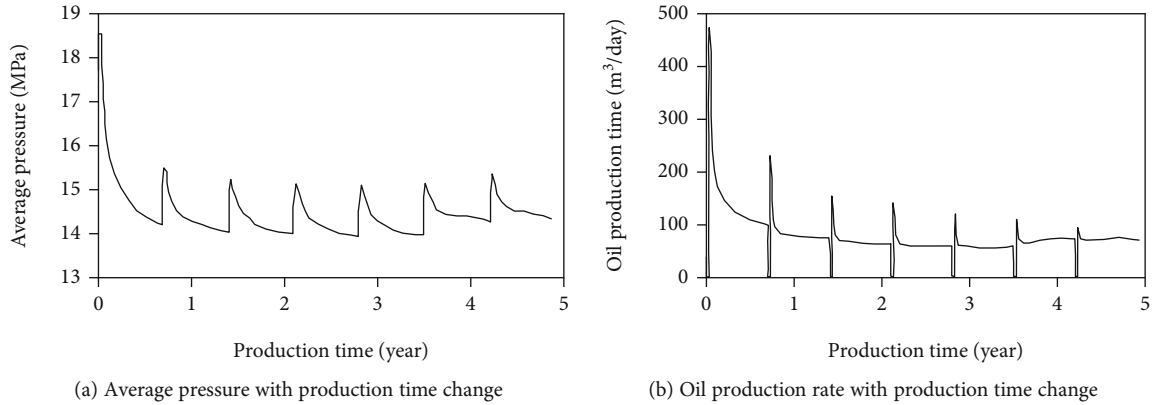
(a) Average pressure with production time change

(b) Oil production rate with production time change

FIGURE 8: Production performance of the optimal CO_2 huff-n-puff scheme.

Before measurement   After CO_2 huff-n-puff   After water flooding
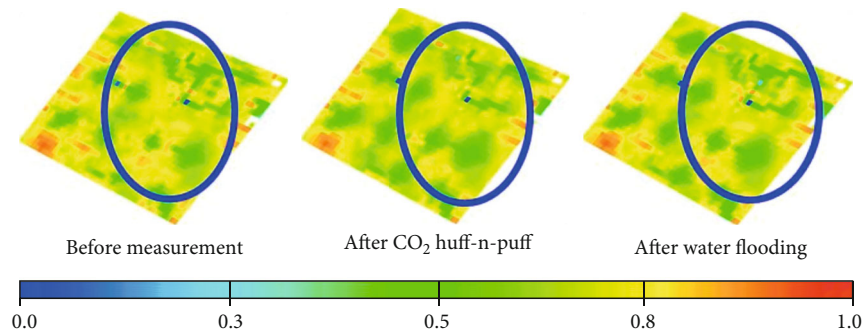
0.0   0.3   0.5   0.8   1.0

FIGURE 9: Remaining oil saturation distributions before and after taking measurements.

pressure and the oil production rate were maintained at a high level. The average pressure and the oil production rate have the same change trend during each cycle and gradually decrease with the increased cycle number. The 8 years oil recovery of CO_2 huff-n-puff and water flooding were 19.07% OOIP and 10.20% OOIP, respectively. The optimal CO_2 huff-n-puff can significantly improve oil recovery by 8.87% compared with water flooding.

The selected optimal scheme was calculated, and the average reservoir pressure and oil production rate of CO_2 huff-n-puff process were shown in Figure 8. For the optimal CO_2 huff-n-puff process, the average reservoir pressure and the oil production rate were maintained at a high level. The average pressure and the oil production rate have the same change trend during each cycle and gradually decrease with the increased cycle number. The 8 years oil recovery of CO_2 huff-n-puff and water flooding were 19.07% OOIP and 10.20% OOIP, respectively. The optimal CO_2 huff-n-puff can significantly improve oil recovery by 8.87% compared with water flooding.

Figure 9 shows the remaining oil saturation distributions before and after CO_2 huff-n-puff and water flooding. Comparing the remaining oil saturations before and after taking measurements, the remaining oil saturation after CO_2 huff-n-puff is much less than that after water flooding. This obviously indicates that the displacement efficiency of CO_2 huff-n-puff is superior to water flooding, which is the main reason why the CO_2 huff-n-puff process is taken.

1st cycle   2nd cycle

4th cycle   7th cycle

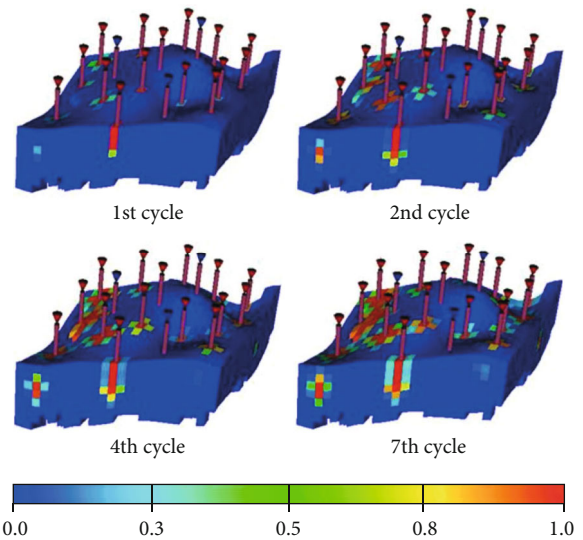0.0   0.3   0.5   0.8   1.0

FIGURE 10: CO_2 saturation distributions of different huff-n-puff cycles.

The CO_2 huff-n-puff process also achieved good sweep efficiency, which also attributes to the good performance of this process. We used CO_2 saturation distributions to approximately illustrate the sweep efficiency degree as shown in Figure 10. With the increase of the CO_2 huff-n-puff cycle, the CO_2 saturation increases but the increase

degree decreases. However, the CO_2 only centralized distributes around the huff-n-puff production well and decreases dramatically away from the production well. This indicates that the CO_2 huff-n-puff process achieves good sweep efficiency only around the production well, where the remaining oil is rich. Thanks to the superior sweep efficiency of the CO_2 huff-n-puff process, the remaining oil around the production well achieves high oil recovery.

5. Conclusions

Sensitivity analysis and multiobjective optimization of CO_2 huff-n-puff process were conducted in this research, and the following conclusions can be drawn:

Single factor sensitivity analyses were conducted, and the influence rules were achieved. The decreased bottom hole pressure results in the increased oil recovery. It indicates that CO_2 solution drive with low bottom hole pressure contributes more on oil recovery than miscible drive with high bottom hole pressure for CO_2 huff-n-puff process.

The single factor influence degree ranking is determined based on the range scores: reopen production time, cycle number, CO_2 injection time, bottom hole pressure, CO_2 injection volume, and soaking time. The contribution degree of soaking time is the least during the whole production period compared with other factors, though it increases oil recovery by CO_2 molecular diffusion mechanism during well shut period obviously.

The optimal CO_2 huff-n-puff scheme was determined using orthogonal experimental design with multifactor influences and multiobjective goals, and it can significantly improve oil recovery by 8.87% OOIP compared with water flooding.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work; there is no professional or other personal interest of any nature or kind in any product, service, and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled.

Acknowledgments

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