

Research Article

Performance Optimization of CO₂ Huff-n-Puff for Multifractured Horizontal Wells in Tight Oil Reservoirs

Mingqiang Hao,¹ Songlin Liao,² Guangming Yu,³ Xinhui Lei,³ and Yong Tang^{1,4} 

¹Research Institute of Petroleum Exploration & Development, PetroChina, Beijing 100083, China

²SINOPEC East China Company, Taizhou, Jiangsu 225300, China

³Research Institute of Petroleum Exploration & Development, Changqing Oilfield Company, PetroChina, Xi'an, Shaanxi 710018, China

⁴State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu, Sichuan 610500, China

Correspondence should be addressed to Yong Tang; tangyong2004@126.com

Received 14 August 2020; Revised 30 September 2020; Accepted 2 November 2020; Published 16 November 2020

Academic Editor: Jinze Xu

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In this paper, the sensitivity factors of CO₂ huff-n-puff for multifractured horizontal wells (MFHWs) in tight oil reservoirs were investigated through an experimental test and numerical simulation. The pressure-volume-temperature (PVT) experiment and the slim tube experiment are used to understand the interaction mechanism between CO₂ and crude oil, and the minimum miscibility pressure (MMP) of the CO₂-crude oil system is 17 MPa. The single-well model was firstly established to analyze the sensitivity factors on production performance of MFHWs by using CO₂ huff-n-puff. The controlling factors of CO₂ huff-n-puff for MFHWs in tight oil reservoirs were divided into three categories (i.e., reservoir parameters, well parameters, and injection-production parameters), and the impact of individual parameter on well performance was discussed in detail. The range of reservoir parameters suitable for CO₂ huff-n-puff of MFHWs is obtained. The reservoir permeability is from 0.1 mD to 1 mD, the reservoir thickness changes from 10 m to 30 m, and the reservoir porosity is from 7% to 12%. Based on the reservoir parameters of the target reservoir, the reasonable well and fracture parameters are obtained. The sensitivity intensity was followed by the horizontal well length, fracture conductivity, fracture spacing, and fracture half-length. CO₂ injection-production parameters are further optimized, and the sensitivity intensity was followed by the single-cycle cumulative CO₂ injection rate, the soaking time, the injection rates, and the production rates. It provides a reference for parameter optimization of CO₂ huff-n-puff for MFHWs in tight oil reservoirs.

1. Introduction

The tight reservoir has gradually become a hot spot of oil and gas exploration and development in recent years. However, due to the poor reservoir properties, the oil recovery factor by the primary depletion is usually less than 10% [1–4]. Advanced horizontal drilling and hydraulic fracturing technologies have obtained economic production of tight formations, but rapid production decline of tight reservoirs is still a major issue [5–7]. Gas injection through horizontal wells has become one of the most promising enhanced oil recovery

(EOR) methods for tight reservoirs [8–10]. Meanwhile, CO₂ injection is one of the most common EOR methods because of its excellent displacing capacity, sweep efficiency, and pressure propagation [11, 12]. CO₂ flooding can greatly improve the shortage of water flooding, and it is an effective way to improve oil recovery [13, 14]. Song and Yang [15] collected core samples from a tight formation with a permeability range of 0.27–0.83 mD to conduct a series of core flooding experiments, and both the near-miscible and miscible CO₂ huff-n-puff processes result in higher development efficiency compared to that of water flooding. Several field applications

of immiscible CO₂ flooding in this reservoir showed poor performance due to the early breakthrough of CO₂ resulting from the existing natural fractures [11, 16].

CO₂ puff-n-huff seems to be a feasible method for improving oil recovery in tight reservoirs. On the one hand, CO₂ huff-n-puff technology has relatively low cost and less gas consumption. On the other hand, the gas channeling risk caused by the reservoir heterogeneity can be greatly reduced, and the injected CO₂ can improve the oil displacement efficiency by expanding crude oil volume, extracting the light component, dissolving into crude oil, and reducing the viscosity of crude oil during its interaction with the reservoir oil [17–20]. Li et al. [21] proposed that CO₂ huff-n-puff is an important method for extra-ultra-low-permeability reservoirs or reservoirs with high water cut. And CO₂ huff-n-puff operations were more commonly applied in North America than in China [22].

Hydraulic fractures can provide a large contact area for the injected fluid, allowing CO₂ to be effectively diffused through the fractures [23]. In combination with the advantages of horizontal well technology and CO₂ stimulation, the Jilin oil field [21, 22], the Parshall Oil Field, and the Elm Coulee Oil Field in the Bakken Formation in the North Dakota part [11, 24] have explored the development of CO₂ huff-n-puff after fracturing in tight oil reservoirs and achieved good development performance. However, current studies on CO₂ huff-n-puff through MFHWs mostly focused on heavy oil reservoirs [25, 26] and complex faulted reservoirs, and there are few studies on parameter optimization of CO₂ huff-n-puff in tight oil reservoirs.

Optimization of the dominated factors of CO₂ huff-n-puff in tight reservoirs is significant for enhancing oil production. Sun et al. [26] measured five sensitivity factors to quantify their effects on CO₂ huff-n-puff effectiveness using the embedded discrete fracture model (EDFM) method. The most important factor is CO₂ diffusivity, followed by the number of cycles, CO₂ injection time, CO₂ injection rate, and CO₂ soaking time. Wang et al. [6] only optimized the operation parameters (i.e., CO₂ injection time, soaking time, and the injected CO₂ amount) by numerical simulation. Yu et al. [27] investigated the individual effects of reservoir permeability, fracture half-length, number of cycles, reservoir heterogeneity, and CO₂ diffusion coefficient for CO₂ injection into the Bakken Formation. The sensitivity study revealed that lower permeability, longer fracture half-lengths, larger number of cycles, and higher molecular diffusivity are favorable for the successful CO₂ huff-n-puff. Zuloaga et al. [28] performed cases studies with four uncertain parameters including matrix permeability, well spacing, well pattern, and fracture half-length with a reasonable range based on the middle Bakken Formation; however, the production parameters are not involved. Alharthy et al. [29] also performed simulation to evaluate the CO₂ huff-n-puff process in the Bakken Formation. However, the effect of uncertainties in matrix permeability and fracture half-length on well performance during CO₂ injection was not investigated. Alfarge et al. [17] applied the data analysis for the reported experimental results obtained from 95 cases of naturally preserved core samples to investigate the effect of 10 parameters which could

enhance or downgrade the CO₂-EOR performance in shale-oil reservoirs. And the design of experiments reported that total organic carbon content (TOC) and exposure time are the two main parameters which control CO₂-EOR success in shale reservoirs. Kerr et al. [30] conducted the sensitivity studies on well communication behavior/impacts, injection gas compositions, injection rates, injection/production cycling, and reservoir fluid types and informed the development strategies about the Eagle Ford Formation.

Therefore, parameter optimization of CO₂ huff-n-puff in tight oil reservoirs is chaotic and incomplete. The aim of this paper is to systematically investigate the influence of the significant parameters on production performance of MFHWs by using CO₂ huff-n-puff in tight oil reservoirs. In this paper, laboratory experiments including the pressure-volume-temperature (PVT) experiment and the slim tube experiment were conducted to evaluate the performance of CO₂ huff-n-puff processes in tight oil reservoirs and further clarify the mechanism of CO₂ injection into crude oil. In addition, we performed numerical simulation to optimize parameters by establishing mechanism models of CO₂ huff-n-puff for MFHWs in the tight oil reservoirs located in the Ordos Basin, China. The main factors of CO₂ huff-n-puff for MFHWs in tight oil reservoirs were divided into three categories: reservoir parameters, horizontal well parameters, and injection-production parameters. The influence of each parameter for CO₂ huff-n-puff was analyzed.

2. Laboratory Experiment

2.1. Materials. The light oil samples were collected from the Ordos Basin, northwestern China, and applied to analyze the phase behavior of the CO₂-crude oil systems. The target reservoir belongs to Chang 8 layers, with an average thickness of 25 m, the average permeability of the reservoir is 0.39 mD, and the average porosity is 7.1%. The basic physical properties of the reservoir are shown in Table 1, and the components of the oil sample is presented in Table 2. Furthermore, the purity of CO₂ used in the experiments is 99.999%.

2.2. Experimental Apparatus. First, the phase behavior of the CO₂-crude oil system was conducted using a PVT cell. Second, the MMP of the CO₂-crude oil system was measured using a traditional slim tube.

A mercury-free DBR PVT system (produced by Canadian BDR Company) was applied to measure the crude oil properties and evaluate the CO₂-crude oil interactions with injected CO₂. The schematic diagram of the DBR instrument is shown in Figure 1. The main part of the PVT cell is a visible, high-pressure, high-temperature glass tube with a volume of 150 ml. The experimental temperature tolerance range of the instrument is 30–200°C, and the test accuracy is 0.1°C. The experimental pressure tolerance is between 0.1 and 70 MPa, and the test accuracy is 0.01 MPa.

The traditional slim tube system is a highly simplified one-dimensional model. Figure 2 shows the schematic of the slim tube experiment device. Through the slim tube model, the MMP of the injected gas and the actual reservoir fluid can be simulated. The value of MMP obtained by the

TABLE 1: The physical properties of the tight oil reservoir.

Parameter	Value
Original formation pressure (MPa)	20.9
Reservoir temperature (°C)	84
Saturation pressure (MPa)	10.18
Crude oil viscosity (mPa·s) (20.9 MPa, 84°C)	1.41
Solution gas-oil ratio (GOR) (Sm ³ /m ³) (0.1 MPa, 20°C)	88.9
Crude oil density (kg/m ³) (0.1 MPa, 20°C)	840

TABLE 2: Components of the oil sample under the reservoir conditions (20.8 MPa, 84°C).

Carbon no.	mol.%	Carbon no.	mol.%	Carbon no.	mol.%
CO ₂	0.05	C ₉	2.24	C ₂₁	1.37
N ₂	1.11	C ₁₀	2.93	C ₂₂	0.91
C ₁	24.53	C ₁₁	2.61	C ₂₃	0.91
C ₂	8.15	C ₁₂	1.69	C ₂₄	1.01
C ₃	11.04	C ₁₃	1.01	C ₂₅	0.96
iC ₄	1.59	C ₁₄	5.12	C ₂₆	0.82
nC ₄	4.06	C ₁₅	2.01	C ₂₇	0.87
iC ₅	2.43	C ₁₆	1.78	C ₂₈	0.82
nC ₅	2.7	C ₁₇	1.78	C ₂₉	0.87
C ₆	1.55	C ₁₈	1.05	C ₃₀	0.73
C ₇	0.8	C ₁₉	0.46	C ₃₁₊	5.95
C ₈	2.73	C ₂₀	1.33	Total	100

slim tube experimental test method is closest to the actual reservoir gas injection. The length of the slim tube is 2000 cm, and the diameter is 3.8 mm. The total pore volume (PV) of the slim tube is 98.92 cm³, the average permeability of the tube is 17.54 D, and the average porosity is 42.73%.

2.3. Experimental Procedures. The preparation processes (including cleaning, leakage testing, and live oil preparation) were carried out before each test.

2.3.1. Phase Behavior Test in CO₂-Crude Oil Systems. When the preparation was completed, the prepared crude oil was injected into the PVT cell under the reservoir conditions (20.9 MPa, 84°C). The properties of the crude oil were measured by changing the pressure and the CO₂ concentrations. The procedures are summarized as follows:

(1) Single Flash Test. The crude oil under the current formation temperature and pressure is simulated, and the oil and gas reach equilibrium instantly. The purpose of the single flash experiment is to obtain basic fluid parameters, such as the gas-oil ratio, volume coefficient, and formation oil density.

(2) Constant Composition Expansion (CCE) Test. The formation temperature is kept constant, and the expansion capacity of the formation fluid is analyzed when the pressure changes.

(3) Swelling Test. Under the current formation pressure and temperature, a certain proportion of CO₂ is injected into the crude oil. According to the designed gas injection times, the injected CO₂ is gradually dissolved completely into the oil. After injection of CO₂, the properties of the crude oil will change, and the system saturation pressure, fluid density, and viscosity will be tested. The effect of injected CO₂ on the current formation fluid system will be studied.

2.3.2. Slim Tube Experiment Test. Experimental test temperature is 84°C. According to the conventional slim tube experimental test method, the MMP should be selected from 4 to 6 points, and there should be two points above the miscible pressure (satisfying the recovery factor above 90%) and two points below the miscible pressure. In this experiment, six injection pressures (11 MPa, 13 MPa, 14 MPa, 16 MPa, 18 MPa, and 20 MPa) will be chosen. During the displacement process, when the volume of injected CO₂ reaches 1.2 times PV of the slim tube at a certain rate (6.2 ml/h), the displacement experiment will be stopped. The recovery rate of the slim tube under different pressures will be measured.

3. Numerical Simulation

3.1. Numerical Model. Based on experimental test analysis, numerical simulation was used to better analyze the mechanism of the CO₂ huff-n-puff process and the sensitivity factors. Based on the laboratory oil analysis results of the single flash tests, constant composition expansion test, and swelling test, a PVT model of the oil sample was built by using the WinProp® module (version 2015), which was developed by Computer Modelling Group Ltd. (CMG).

Then, the slim tube model was developed using the GEM® module (CMG, version 2015) to match the MMP value. A reservoir model with MFHWs was further established in the GEM® module (CMG, version 2015) to analyze the effect of parameters and optimize the parameters of CO₂ huff-n-puff for MFHWs in tight oil reservoirs.

To better describe the properties of the oil sample and improve the calculation efficiency, the original components of the oil sample were divided into seven pseudocomponents using the WinProp® module, including CO₂, N₂, C₁, C₂-C₃, C₄-C₆, C₇-C₁₅, and C₁₆-C₃₁₊. More detailed data for the Peng-Robinson (PR) Equation Of State (EOS) are shown in Table 3. The relative permeability curves were taken from the experimental statistics of the core flood tests, shown in Figure 3. The relative permeability curves are assumed to be the same in the slim tube model and single-well model.

3.1.1. Slim Tube Model. The parameters of the slim tube model are consistent with the experiment. The dimension (length, width, and height) of the model is 20 m × 0.0038 m × 0.0038 m. The grid block is 0.25 m × 0.0038 m × 0.0038 m in x, y, and z directions, respectively. There is one production well at the beginning (x = 1) and one injection well at the end (x = 80). The one-dimensional model is shown in Figure 4. The model properties (reservoir temperature, permeability, and porosity), injection pressures (11 MPa,

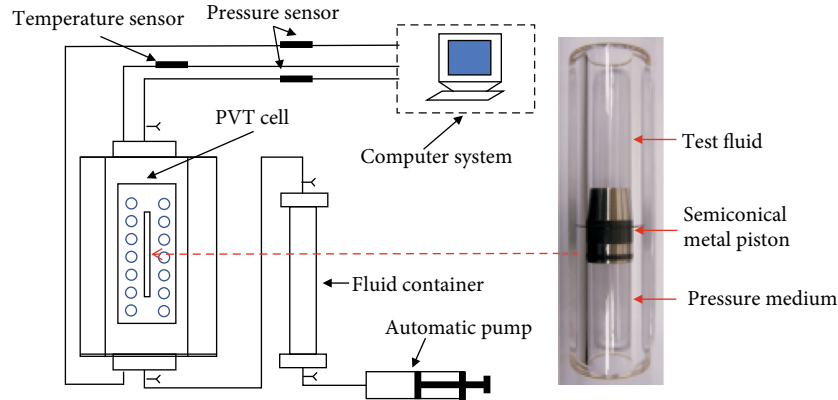


FIGURE 1: Schematic of the experimental setup for the property tests of the CO₂-crude oil system.

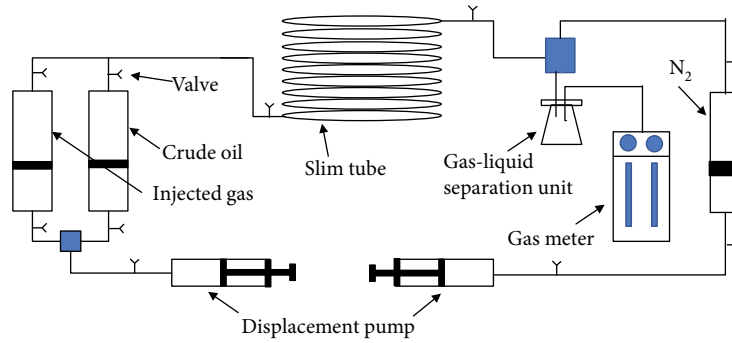


FIGURE 2: Schematic diagram of the slim tube experiment device.

TABLE 3: Properties of pseudocomponents of the oil sample.

Components	Molar fraction	Critical pressure (atm)	Critical temperature (K)	Acentric factor	Molar weight (g/mol)
CO ₂	0.0005	72.80	304.20	0.23	44.01
N ₂	0.0111	33.50	126.20	0.04	28.01
CH ₄	0.2454	45.40	190.60	0.01	16.04
C ₂ -C ₃	0.1920	44.53	344.16	0.13	38.14
C ₄ -C ₆	0.1233	34.92	451.05	0.22	67.46
C ₇ -C ₁₅	0.2115	22.81	651.59	0.38	165.70
C ₁₆ -C ₃₁₊	0.2163	11.91	826.44	0.73	394.18

13 MPa, 14 MPa, 16 MPa, 18 MPa, and 20 MPa), and injection rate were the same as those of the experiment test.

3.1.2. Single-Well Model. The mechanism model of CO₂ huff-n-puff for MFHWs in tight oil reservoirs was established to study the sensitivity factors combined with the physical properties and fluid characteristics of the tight reservoir.

In order to consider the actual production situation and avoid the impact of the reservoir boundary on the CO₂ huff-n-puff, compositional models incorporated with Local Grid Refinement (LGR) of MFHWs for the tight reservoir were established. The dimension of the model (length, width, and height) is 2440 m × 1640 m × 26 m. The grid block is 40 m × 40 m × 2 m in *x*, *y*, and *z* directions. The single horizontal well is in the central area of the model with planar hydraulic fractures along the well, as shown in Figure 5.

The basic reservoir parameters for the simulation are summarized in Table 4. The horizontal well parameters and injection-production parameters are listed in Table 5. During the production stage, the minimum bottom-hole pressure (BHP) was set to 11 MPa (greater than saturation pressure 10.18 MPa).

3.2. Design of Schemes. Accordingly, the optimal values of these parameters were obtained to quantify the effects of several operation parameters [31]. There are 12 parameters which are divided into three categories, including reservoir parameters, horizontal well parameters, and injection-production parameters. Design of schemes are shown in Table 5. Each parameter includes 3 to 5 groups of scenarios, and each scenario is compared with depletion production.

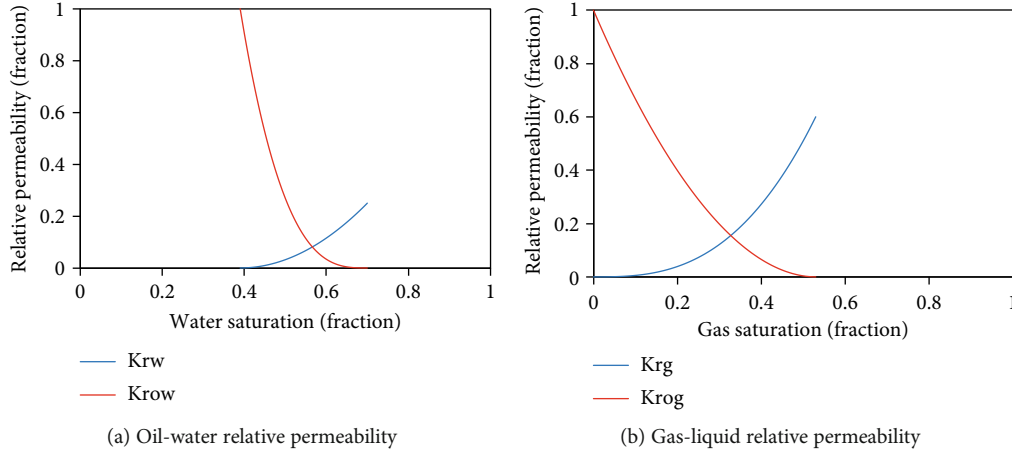


FIGURE 3: The relative permeability curves in the single horizontal well model.

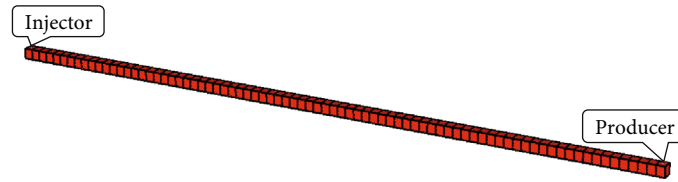


FIGURE 4: Schematic of the slim tube model.

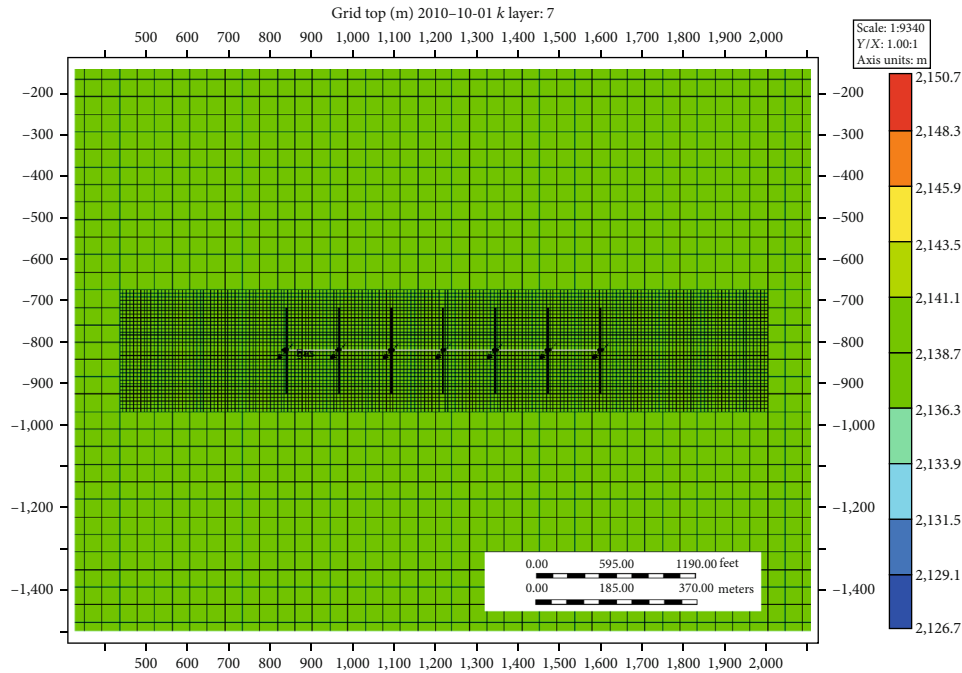


FIGURE 5: Planar grid distribution of the single horizontal well model.

The CO_2 injection timing is optimized based on the daily oil rate of depleted production. It is concluded that the appropriate delay of gas injection timing will help increase the production of CO_2 huff-n-puff [32–34].

Three indexes of the oil exchange rate, incremental oil production [31], and incremental oil recovery factor [28] were used to evaluate the effect of CO_2 huff-n-puff. The oil

exchange rate is defined as the ratio of injected quality of CO_2 and the produced oil quality. The incremental oil production is defined as the difference of cumulative oil production between the depletion production and the CO_2 huff-n-puff production. The incremental oil recovery factor is defined as the difference of the oil recovery factor between the depletion production and the CO_2 huff-n-puff production.

TABLE 4: Reservoir properties used for the simulation.

Properties	Value
Initial reservoir pressure (MPa)	20.9
Reservoir temperature (°C)	84
Matrix porosity	7.1%
Matrix permeability (mD)	0.39
Saturation pressure (MPa)	10.18

4. Results and Discussion

4.1. Phase Behaviors of the CO₂-Crude Oil System

4.1.1. Single Flash Test. The single flash test results of crude oil are obtained by using the PVT test combined with numerical simulation obtained, shown in Table 6. The testing results agree with the field situation, and the relative error of the numerical simulation is less than 5%.

4.1.2. CO₂-Crude Oil Interaction Behaviors. When the proportion of injected CO₂ reaches 50% compared with the original reservoir fluid, the saturation pressure of the crude oil can increase by 7.6 MPa. The crude oil expands by 1.35 times. The viscosity reduction is close to 30%, and the crude oil system becomes lighter. The experimental test results are shown in Table 7. Therefore, it can be concluded that injecting CO₂ into the target reservoir can effectively increase formation energy and reduce viscosity of crude oil.

4.2. CO₂ Miscibility Characteristics

4.2.1. MMP Test. Through the slim tube experiment test and numerical simulation, the MMP of the CO₂-crude oil system is determined to be 17 MPa, and the corresponding recovery factor is above 90%. The test results are shown in Table 8 and Figure 6.

4.2.2. Interphase Mass Transfer Mechanism of the CO₂-Crude Oil System. At the formation temperature, three pressure points were selected in the slim tube model, 11 MPa (less than the miscible pressure), 16 MPa (close to the miscible pressure), and 20 MPa (greater than the miscible pressure). The CO₂ injection volume was 0.6 PV.

More CO₂ will dissolve in the oil with a faster dissolution rate under greater injection pressure, shown in Figure 7(a). The amount of light components (C1) extracted by CO₂ also becomes greater (Figure 7(b)). The effect of viscosity reduction is more obvious (Figure 7(c)), and the interfacial tension of oil and gas phases (2 phases) is significantly reduced (Figure 7(d)). When the injection pressure is 20 MPa (greater than the miscible pressure), the viscosity can be reduced from 1.41 mPa·s to an average of 0.3 mPa·s, and the viscosity reduction can reach 78.7%. The interfacial tension of the displacement front is reduced to 0 dyne/cm.

4.3. Effect of Reservoir Parameters

4.3.1. Reservoir Permeability. The timing of CO₂ huff-n-puff is determined as the daily oil rate of depletion production is 1.5 m³/d. As shown in Figure 8, the permeability is enhanced

by 10 times and the cumulative oil production is increased by 3 to 4 times in the tight reservoir.

When the permeability varies from 0.1 mD to 1 mD, the oil exchange rate changes significantly. If the permeability is small enough, the diffusion of injected CO₂ is very difficult at the bottom of the hole, resulting in a rapid increase in the pressure around the well, pushing the formation crude oil farther. When the formation permeability exceeds 1 mD, CO₂ diffuses rapidly at the bottom of the wellbore, and the BHP decreases rapidly, leading to a decrease in relative incremental oil production. When the reservoir permeability is between 0.1 mD and 1 mD, it is more suitable for CO₂ huff-n-puff through MFHWs.

4.3.2. Reservoir Thickness. To evaluate the influence degree of CO₂ huff-n-puff on the reservoir, the influence of reservoir thickness will be evaluated based on the variation of the oil exchange rate and incremental oil recovery factor. Figure 9 shows that the oil exchange rate firstly increases and then decreases with the increase in the reservoir thickness. When the formation thickness is 26 m, the oil exchange rate gets the maximum value and the incremental oil recovery factor has a decreasing tendency. It can be obtained that the reservoir thickness continues to increase, and the effect of CO₂ huff-n-puff is less obvious. For the target tight reservoir, when the reservoir thickness is between 10 m and 30 m, it is better to use the CO₂ huff-n-puff technology to enhance oil recovery.

4.3.3. Reservoir Porosity. Similar to the evaluation of reservoir thickness, the influence of reservoir porosity on the CO₂ huff and puff effect will be evaluated based on the variation of the oil exchange rate and incremental oil recovery factor.

The timing of CO₂ huff-n-puff is determined as the daily oil rate of depletion production is 1.5 m³/d. With the increase in reservoir porosity, the oil exchange rate gradually increases, but the increasing trend gradually slows down, and the incremental oil recovery factor gradually decreases, as shown in Figure 10.

For the target tight reservoir, when the porosity of the reservoir is between 7% and 12%, it is better to use the CO₂ huff-n-puff technology of MFHWs to improve oil recovery.

4.4. Effect of Horizontal Well Parameters

4.4.1. Length of the Horizontal Well. The timing of CO₂ huff-n-puff is determined as the daily oil rate of depletion production is 1 m³/d. As the horizontal well length increases, the oil exchange rate and incremental oil production show an increasing trend, but the increasing trend is gradually slowing down as shown in Figure 11.

When the horizontal well is short, the BHP rises quickly after CO₂ injection, and the CO₂ diffusion rate is very slow. Therefore, the oil exchange rate and incremental oil production are relatively low. If the length of the horizontal well is long, the contact area between CO₂ and crude oil is increased, but the supplemental formation energy is weakened, and the friction of fluid in the wellbore will be increased, thus reducing the increase in productivity. When the length of the

TABLE 5: Twelve parameters used in the simulation cases.

Parameter types	Parameter	Design of schemes	Basic parameter value
Reservoir parameters	Permeability (mD)	0.039, 0.1, 0.39, 1, 3.9	0.39
	Thickness (m)	6, 14, 26, 34	26
	Porosity (%)	3, 7.1, 12, 15	7.1
	Length (m)	240, 480, 720, 960, 1200	720
Horizontal well parameters	Fracture half-length (m)	60, 100, 124, 140	100
	Fracture spacing (m)	80, 120, 180, 240	120
	Fracture conductivity (mD·m)	10, 20, 30, 50	30
	Total CO ₂ injection (t)	500, 750, 1000, 1500, 2500, 4000	1500
Injection-production parameters	CO ₂ injection rate (t/d)	30, 50, 75, 100, 150	50
	Soaking time (d)	5, 10, 20, 30, 50	20
	Production rate (m ³ /d)	5, 10, 20, 30, 50	50
	Cycles	1, 2, 3, 4, 5	1

TABLE 6: Single flash test results of crude oil.

Test items	Experimental value	Simulation value	Relative error (%)
Gas-oil ratio (GOR) (Sm ³ /m ³)	85.2	82.4	3.24
Crude oil density (kg/m ³) (20.9 MPa, 84°C)	724.8	730.5	0.79
Crude oil density (kg/m ³) (0.1 MPa, 20°C)	840	845	0.68
Crude oil viscosity (mPa·s) (20.9 MPa, 84°C)	1.41	1.407	0.19
Saturation pressure (MPa)	10.18	10.41	2.30

TABLE 7: The CO₂-crude oil interactions at formation temperature.

CO ₂ mol percentage (%)	Saturated pressure (MPa)	Coefficient of expansion	Viscosity (mPa·s)
0	10.18	1	1.41
12.3	11.45	1.033	1.36
25.4	13.21	1.142	1.28
35.6	14.85	1.195	1.17
46.5	16.65	1.311	1.05
60.4	20.21	1.489	0.90
71.2	24.62	1.794	0.72

TABLE 8: Test results of MMP.

Displacement pressure (MPa)	Slim tube experimental recovery (%)	Numerical simulation recovery (%)	Relative error (%)
11	72.56	71.90	-0.66
13	79.70	77.80	-1.90
14	82.20	79.64	-2.56
16	89.10	85.53	-3.57
18	92.16	90.49	-1.67
20	93.12	95.04	1.92

horizontal well is between 700 m and 1200 m, the oil exchange rate is above 0.5.

4.4.2. Fracture Half-Length. The result of the influence is shown in Figure 12: the oil exchange rate and incremental

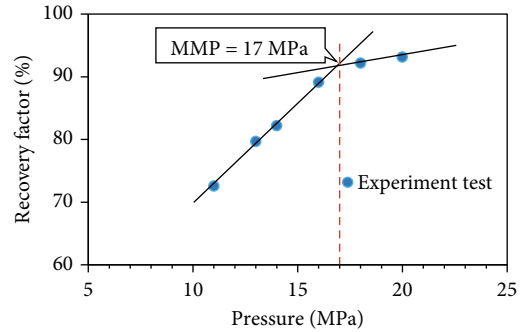


FIGURE 6: Experiment test results of MMP.

oil production are gradually increasing with the fracture half-length increased, but the trend is gradually slowing down. The half-length of the fracture increases from 100 m to 140 m, and the oil increase rate only increases by 12.4 t, which has little impact on CO₂ huff-n-puff. Meanwhile, the longer the half-length of the fracture, the more difficult it is to operate. It is concluded that the fracture half-length is about 100 m and the oil increase effect is better.

4.4.3. Fracture Spacing. Three groups of scenarios were defined (fracture spacing, 80 m (10 fractures), 120 m (7 fractures), 180 m (5 fractures), and 240 m (4 fractures)), and the results are shown in Figure 13. When the fracture spacing was reduced, the oil exchange rate and incremental oil production are gradually increasing. Overall, the fracture spacing changes from 240 m to 80 m, and the oil increase is about 50 t, which has little impact on CO₂ huff-n-puff. The

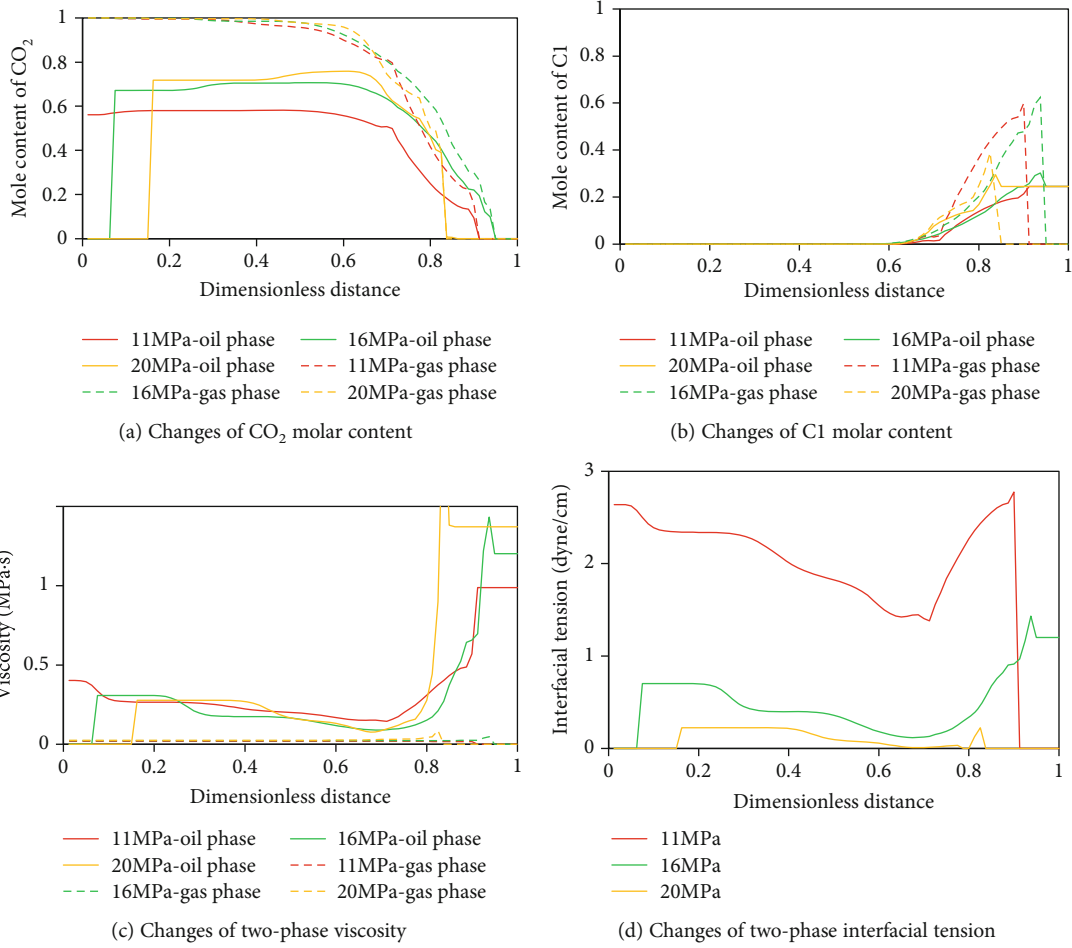


FIGURE 7: Changes of two-phase fluid properties at different pressures.

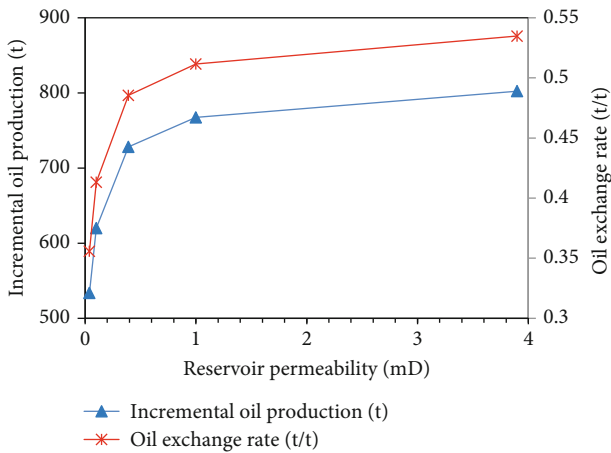


FIGURE 8: Variations of the incremental oil production and oil exchange rate at different reservoir permeability.

fracture spacing is about 120 m, the oil exchange rate reaches 0.51, and the EOR effect is better.

4.4.4. Fracture Conductivity. As shown in Figure 14, the cumulative oil production will be increased with larger fracture conductivity. However, the oil exchange rate and the

incremental oil production show a trend of increasing first and then decreasing, and an inflection point appeared around 30 mD-m. It is concluded that the fracture conductivity is 20 mD-m-30 mD-m, the oil exchange rate reaches 0.51, and the oil increase effect is better.

4.5. Effect of Injection-Production Parameters

4.5.1. Cumulative CO_2 Injection Rates. The length of the horizontal well is 720 m, and the timing of CO_2 huff-n-puff is determined as the daily oil rate of depletion production is $1 \text{ m}^3/\text{d}$. The CO_2 injection rate is 50 t/d ($2.7 \times 10^4 \text{ m}^3/\text{d}$), and other conditions are consistent. Figure 15 shows that a large amount of CO_2 injection rates will increase more oil production. And the incremental oil production shows an increasing trend, but the trend gradually slows down. The oil exchange rate increases firstly and then decreases. When the cumulative CO_2 injection rates are between 750 t and 1000 t, the oil exchange rate reaches the maximum value. When the oil exchange rate is combined with the incremental oil production and economic benefits, the optimal injection amount should be selected after the maximum of the exchange rate. Therefore, the injection volume from 1000 t to 2500 t is preferred, and the economic benefit is better.

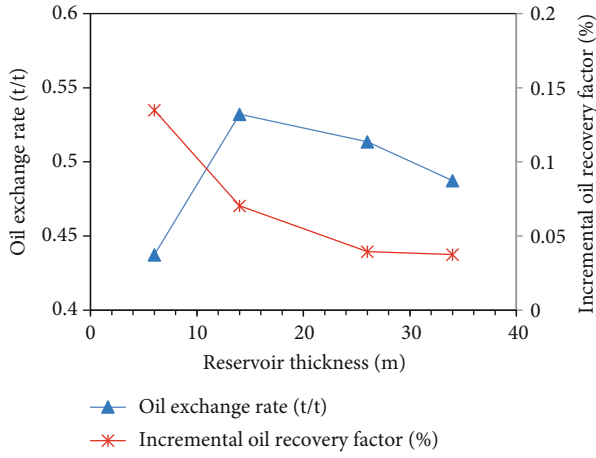


FIGURE 9: Oil exchange rate and incremental oil recovery through CO₂ huff-n-puff under different reservoir thickness.

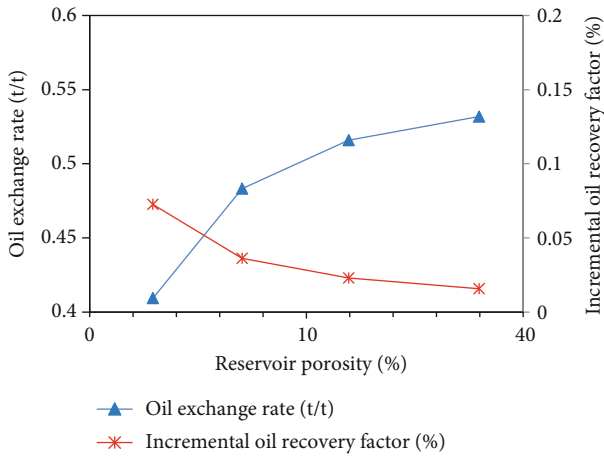


FIGURE 10: Oil exchange rate and incremental oil recovery through CO₂ huff-n-puff under different reservoir porosity.

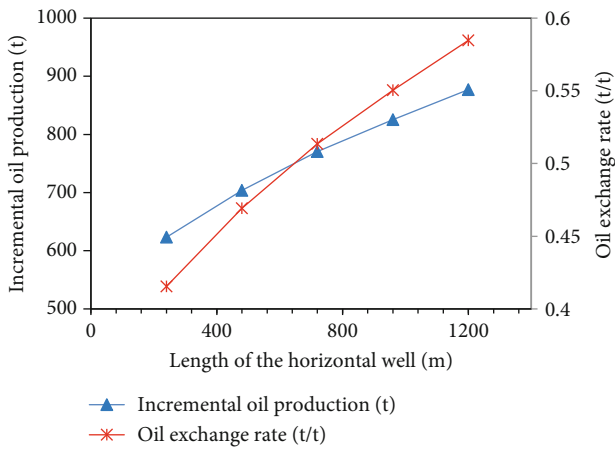


FIGURE 11: Incremental oil production and oil exchange rate through CO₂ huff-n-puff under different horizontal well lengths.

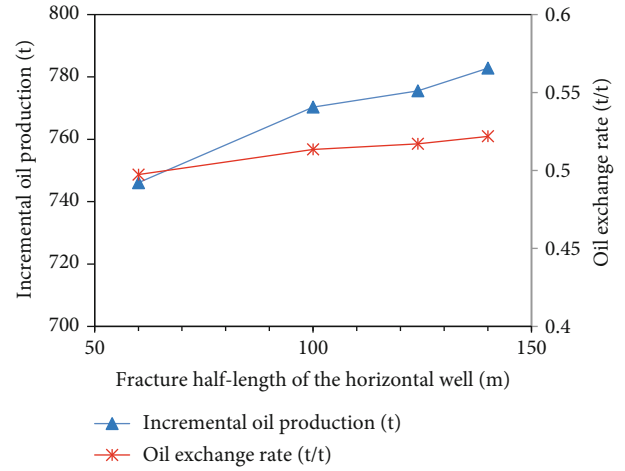


FIGURE 12: Incremental oil production and oil exchange rate through CO₂ huff-n-puff under different fracture half-lengths of the horizontal well.

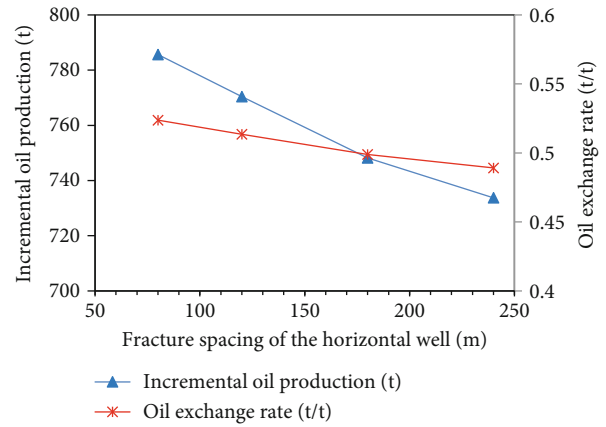


FIGURE 13: Incremental oil production and oil exchange rate through CO₂ huff-n-puff under different fracture spacing along the horizontal wellbore.

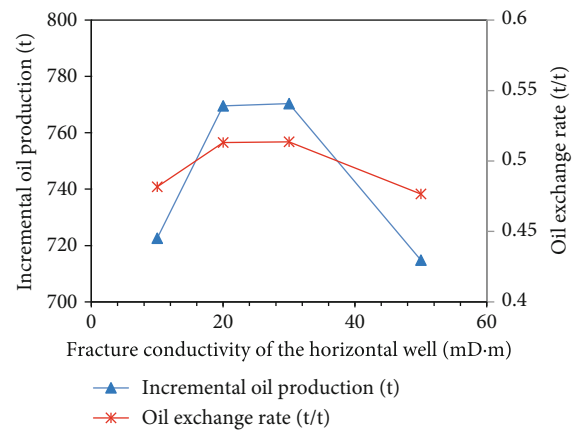


FIGURE 14: Incremental oil production and oil exchange rate through CO₂ huff-n-puff under different fracture conductivity.

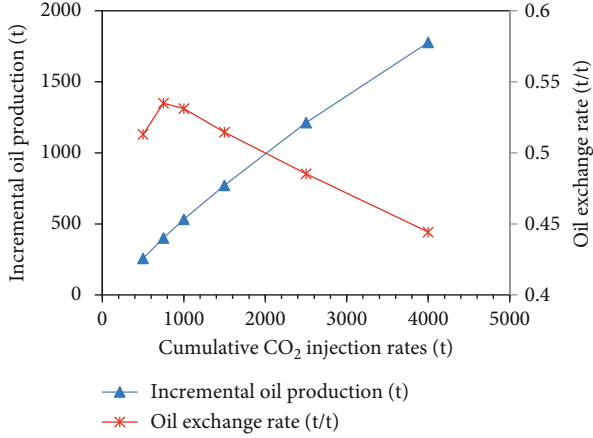


FIGURE 15: Incremental oil production and oil exchange rate through CO₂ huff-n-puff under different total CO₂ injection volumes.

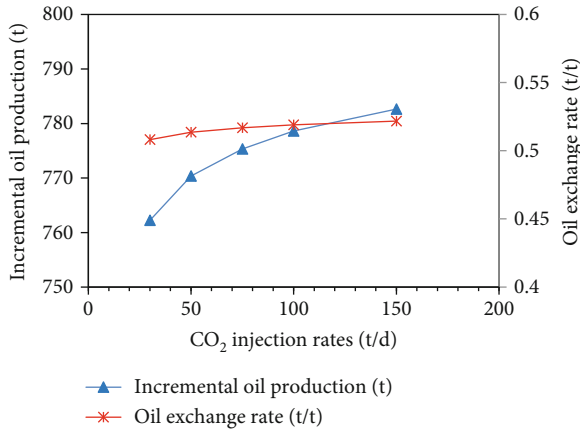


FIGURE 16: Incremental oil production and oil exchange rate through CO₂ huff-n-puff under different CO₂ injection rates.

4.5.2. CO₂ Injection Rates. The cumulative CO₂ injection rates are determined to be 1500 t (83.1×10^4 m³). The oil exchange rate and the incremental oil production show an increasing trend with higher CO₂ injection rates, but the trend gradually slows down as shown in Figure 16. The injection rates increase from 30 t/d to 150 t/d, and the incremental oil production increases by 20 t. Also, the oil exchange rate increases by 0.013 t/t, which has little impact on the oil production. When the injection rate is 50 t/d, the oil exchange rate can reach 0.51 and the EOR efficiency is better.

4.5.3. Soaking Time. Figure 17 indicates that the oil exchange rate and the incremental oil production present an increasing trend with longer soaking time, but the trend gradually slows down. The soaking time is increased from 5 d to 50 d, and the oil increase rate is increased by 40 t. In addition, the oil exchange rate is increased by 0.028 t/t, which has little impact on the oil production. When the soaking time reaches 20 days, the oil exchange rate can reach 0.51 and the EOR performance is better.

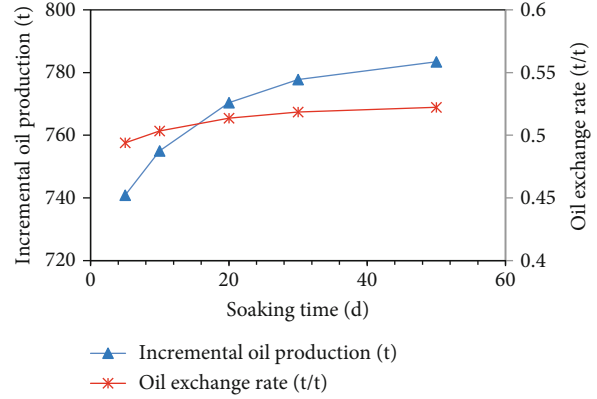


FIGURE 17: Incremental oil production and oil exchange rate through CO₂ huff-n-puff under different soaking times.

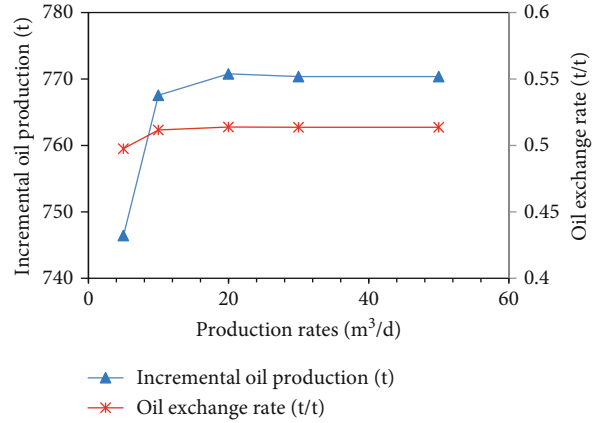


FIGURE 18: Incremental oil production and oil exchange rate through CO₂ huff-n-puff under different production rates.

4.5.4. Production Rates. Under the restriction of the minimum BHP of 11 MPa, the results are shown in Figure 18: when the production rate is 20 m³/d, the oil exchange rate and the incremental oil production reach the maximum value. The production rate increases from 5 m³/d to 50 m³/d, the oil increase rate only increases by 24 t. And the oil exchange rate increases by 0.016 t/t, so that the production rate has little influence on CO₂ huff-n-puff. Based on the minimum BHP, the production rate should be greater than 20 m³/d to fully release formation energy.

4.5.5. Cycles. Five cases are designed and the cycles change from 1 to 5 cycles, and the cumulative CO₂ injection rate of a single cycle is 1500 t (83.1×10^4 m³). The timing of CO₂ huff-n-puff for the first cycle is determined as the daily oil rate of depletion production is 1 m³/d, and the single cycle time is 2 years. Other control conditions are kept constant for all cases. The results are shown in Figure 19. The cumulative incremental oil production increases as the cycles increase, but the incremental oil production of the single cycle gradually decreases. The cumulative oil exchange rate was higher than 0.4 t/t in 3 cycles of CO₂ huff-n-puff, and the decline rate for the single cycle was less than 35%. The overall EOR performance is good.

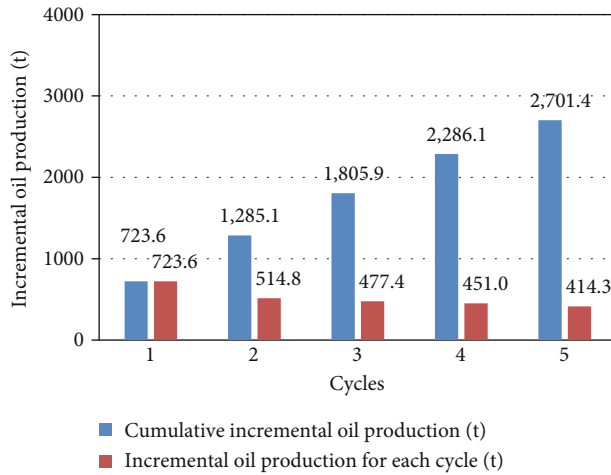


FIGURE 19: Incremental oil production through CO₂ huff-n-puff under different cycles.

4.6. Sensitivity Analysis. The purpose of sensitivity analysis is to determine the quantitative effect of different parameters on production performance. Identifying the parameters that have an important impact on CO₂ huff-n-puff performance in the lab scale would give a good prediction for CO₂-EOR success or failure depending on reservoir properties prior to the field application. Also, it would help to optimize the operating parameters in the field scale [14, 17]. In this study, design of experiments for the factors affecting the performance of the CO₂-EOR huff-n-puff process in the lab scale has been conducted. The main controlling factors affecting CO₂ huff-n-puff of MFHWs in tight oil reservoirs are determined. Based on reservoir parameters and choosing the oil exchange rate as the evaluation index, the dominated factors of the horizontal well and injection-production parameters were analyzed by using a range analysis method.

According to the influence of each parameter, the maximum and minimum values of the oil exchange rate are obtained, and the extreme value of the oil exchange rate of each parameter within the scope of the scheme design is obtained. The greater the variation of the oil exchange rate, the greater the influence of this parameter on CO₂ huff-n-puff will be. Figure 20 shows that the length of the horizontal well is the main controlling factor of the horizontal well by CO₂ huff-n-puff in tight oil reservoirs, followed by fracture conductivity, fracture spacing, and fracture half-length. Figure 21 shows that the cumulative CO₂ injection rate is the dominated factor of single-cycle injection-production parameters by CO₂ huff-n-puff through horizontal wells in tight oil reservoirs, followed by the soaking time, the injection rates, and the production rates.

5. Conclusions

In this paper, laboratory experiments and numerical simulation analysis of the reservoir are carried out to study the mechanism and performance optimization of CO₂ huff-n-puff for MFHWs in tight oil reservoirs to provide theoretical support for CO₂ huff-n-puff technology.

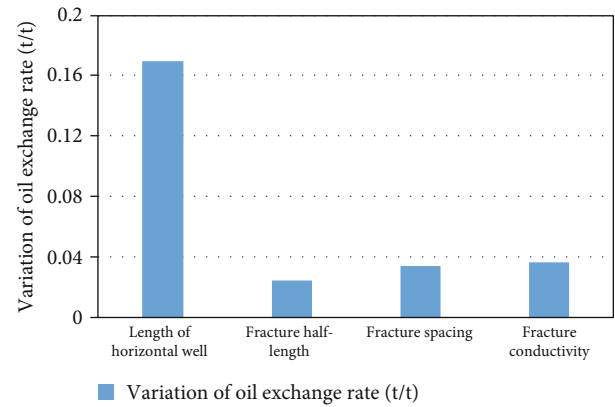


FIGURE 20: Variation distribution of the oil exchange rate with horizontal well parameters.

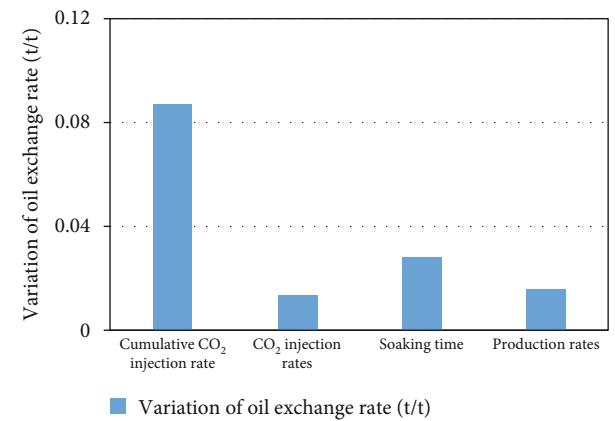


FIGURE 21: Variation distribution of the oil exchange rate of single-cycle injection-production parameters.

- (1) The PVT experiment and the slim tube experiment proved that CO₂ injection could effectively improve the properties of crude oil, and the CO₂-crude oil system can easily achieve the miscibility condition (the MMP is 17 MPa). From the mechanism of the interaction between CO₂ and crude oil, the feasibility of CO₂ injection to improve oil recovery in this reservoir was confirmed
- (2) A single-well numerical model is established to analyze the influence of reservoir parameters, horizontal well parameters, and injection-production parameters on the CO₂ huff-n-puff technology. The reasonable parameters suitable for CO₂ huff-n-puff through MFHWs in the tight oil reservoir are obtained. The reservoir permeability is 0.1 mD to 1 mD, the reservoir thickness is 10 m to 30 m, and the reservoir porosity is 7% to 12%
- (3) Based on the reservoir parameters, the reasonable well and fracture parameters are obtained. The horizontal well length is 700 m to 1200 m, the fracture half-length is 100 m, the fracture spacing is 120 m, and the fracture conductivity is 30 mD·m. CO₂

injection-production parameters are further optimized. The CO₂ injection volume for a single cycle is 1000 t to 2500 t, the CO₂ injection rate changes from 50 to 100 t/d ($2.7 - 5.5 \times 10^4$ m³/d), and the soaking time is between 20 d and 30 d. The production rate is greater than 20 m³/d, and the two or three huff-n-puff cycles are preferred

- (4) The sensitivity analysis of influencing factors was carried out. The main controlling factors are the length of the horizontal well and the cumulative CO₂ injection rates

Data Availability

Data is included in the manuscript.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgments

This work was supported by the National Science and Technology Major Projects of China (2016ZX05016), Major Special Projects of PetroChina Company Limited (2014E-3602), National Natural Science Foundation of China (51974268), and Key Project of Sichuan Province Science and Technology Department (2019YJ0423).

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