



ARTICLE

Numerical Simulation of CO₂ Huff-and-Puff Mechanism and CO₂/N₂ Synergistic Huff-and-Puff in the Edge-Bottom Water Reservoirs

Xiutai Cao¹, Yuxin Sun¹, Bowen Shi¹, Hao Zhang¹, Hongli Tang¹, Yongbin Bi^{1,2} and Huiying Zhong^{1,3,*}

¹Key Laboratory for Enhanced Oil & Gas Recovery of the Ministry of Education, Northeast Petroleum University, Daqing, 163318, China

²Nanpu Operation Area, PetroChinaJidong Oilfield Company, Tangshan, 063200, China

³Key Laboratory of Reservoir Stimulation, China National Petroleum Corporation, Daqing, 163318, China

*Corresponding Author: Huiying Zhong. Email: zhhy_nepu@nepu.edu.cn

Received: 11 October 2025; Accepted: 16 December 2025; Published: 12 July 2026

ABSTRACT: With the steady advancement of China's "Dual-Carbon" goals, CO₂ huff-and-puff technology has become one of the mainstream methods for enhancing oil recovery (EOR) in oilfields. However, differences in sweep radius of CO₂, CO₂-oil interaction mechanisms, injection parameters, and huff-and-puff modes between conventional heavy-oil and light-oil reservoirs still require further investigation. The NP oilfield consists of an upper heavy-oil zone and a lower light-oil zone, with the reservoir inclined at a certain angle. Taking this oilfield as the study area, a positively rhythmic reservoir geological model was established. A compositional numerical simulation approach was employed to analyze the sweep radius of CO₂ and the mechanisms of oil-saturation reduction of various huff-and-puff cycles under edge-water reservoir conditions. To address the issue of insufficient energy supply in well groups within closed fault blocks, the effects of synergistic CO₂-N₂ huff-and-puff on the development performance of conventional heavy-oil and light-oil reservoirs were further investigated. The results show that the sweep radius of CO₂ huff-and-puff in heavy-oil reservoirs is significantly larger than that in light-oil reservoirs. Under a 10 m oil-column height, the maximum sweep radius reaches 100 m for heavy oil reservoirs, compared with 65 m for light oil reservoirs. Moreover, the average oil-saturation reduction per cycle in heavy-oil reservoirs is 0.58% higher than that in light-oil reservoirs. For well groups in closed fault blocks with weak energy supply, synergistic CO₂-N₂ huff-and-puff can effectively enhance oil recovery, benefiting from the gravity override effect of N₂. Based on numerical simulation, the optimal CO₂: N₂ injection ratios for synergistic huff-and-puff were determined to be 2.1:1 for heavy oil and 1.67:1 for light oil. These findings provide important theoretical support for optimizing CO₂ flooding development strategies in reservoirs of similar types.

KEYWORDS: CO₂ huff-and-puff; dip angle; swept radius; CO₂/N₂ synergistic huff-and-puff; edge-bottom water reservoir

1 Introduction

Global temperatures continue to rise due to the emission of greenhouse gases [1–3]. The Paris Agreement seeks to keep the rise in global temperatures well below 2°C compared to pre-industrial levels [4,5]. This is the reason why an increasing number of countries and regions have adopted carbon neutral targets, which emphasize the significance of emission reduction technologies [6–10]. Driven by the global energy transition and carbon neutrality goals, CO₂ huff-and-puff has become a key technological choice for the



low-permeability reservoir, tight reservoir, and strong edge-bottom water reservoir. This is because CO₂ huff-and-puff offers dual advantages of enhanced oil recovery (EOR) and carbon capture, utilization, and storage (CCUS) [11–13]. In recent years, there have been new insights for the study of the reservoirs with dip angle and edge-bottom water. To address the challenges of high viscosity and poor mobility of heavy oil as well as bottom water breakthrough, Xu et al. [14] developed a numerical model based on the Liuguanzhuang Oilfield in Dagang. The characteristics and production behavior of CO₂ huff-and-puff in horizontal wells of heavy oil reservoirs are investigated. The results demonstrated that CO₂ formed a viscosity reduction zone above the horizontal well. With increase of huff-and-puff cycles, the enhancement in the oil drainage area gradually decreases. Zhao et al. [15] combined large-scale physical simulations and numerical modeling. They investigated key parameters and development performances of CO₂ huff-and-puff in multistage fractured horizontal wells in tight reservoirs. Their innovation demonstrated that fractures can reduce flow resistance and enhance CO₂ sweep efficiency through pressure field visualization. Thus, this provides evidence of significantly enhanced oil recovery. Shabib-Asl et al. [16] investigated the performance of CO₂ foam huff-and-puff and its impact on recovery in tight oil reservoirs by combining laboratory experiments with numerical simulations. This study addresses the problems of extremely low porosity and permeability. The results indicate that CO₂ foam huff-and-puff can significantly enhance oil recovery. Key influence parameters include production time, injection time, and soaking time. Injection rate and incremental injection rate have relatively minor effects. Afari et al. [17] addressed the issue of insufficient understanding of key operational parameters during CO₂ injection for developing unconventional reservoirs. Through component simulation and response surface methodology (RSM), five core parameters are studied. This identifies that bottomhole pressure and production cycle exerted the greatest influence (longer soaking time reduced oil recovery). Following optimization, incremental recovery exceeded 7%. Wei and Bai [18] addressed the issue of low recovery in North American shale formations by integrating laboratory experiments, reservoir numerical simulations, and pilot tests. The impact of molecular diffusion mechanisms of CO₂ huff-and-puff in the Bakken formation is investigated. Their findings revealed CO₂ diffusion was poor within this formation. It also explained the macroscopic-microscopic diffusion differences in unconventional reservoirs and the influence on enhanced oil recovery. Tang et al. [19] analyzed the dynamic characteristics, influence factors of CO₂ huff-and-puff. Their analyses also revealed the contribution of sweep pattern to recovery through laboratory experiment. The results showed that CO₂ injection volume and development speed are the main factors influencing the oil recovery. A reasonable soaking time exists in CO₂ huff-and-puff. The oil recovery of CO₂ huff-and-puff is primarily contributed by flow sweep and diffusion sweep. The diffusion sweep contributes more during the soaking time. Wang et al. [20] conducted laboratory experiments on N₂ and CO₂ mixture huff-and-puff. They explored the influence of injection ratio and injection sequence on oil increment and water cut control. The problems of excessive water production during the development of edge-water fault-block reservoirs are studied. The results show that N₂ huff-and-puff has the most obvious effect on water cut control. CO₂ huff-and-puff has the best effect on oil increment, and the optimal injection ratio of N₂ and CO₂ is 7:3.

In conclusion, existing studies have shown the effectiveness of CO₂ huff-and-puff. It can control water cut and stabilize oil production in reservoirs with dip angles. However, relatively few studies exist on the huff-and-puff behaviors of conventional heavy oil and light oil groups. Comparative analyses in the same edge-bottom water reservoir are lacking. In this work, a numerical model that differs from prior studies in three aspects was established. First, taking NP oilfield—which simultaneously developed both light and conventional heavy oil groups—as an example, a positive-rhythm reservoir geological model with inclination was established. Second, numerical simulations were conducted using a component model. It was used to analyze the CO₂ swept radius and the mechanism of oil saturation reduction in the edge water reservoir

during different huff-and-puff cycles. It also enabled a comparison between heavy and light oils under identical conditions. Third, for small blocks of the NP oilfield characterized by limited natural energy, the study investigated the impact of CO₂–N₂ synergistic huff-and-puff on the development of conventional heavy and light oils. It also determined the optimal CO₂/N₂ injection ratio for different oil viscosities. These aspects will be discussed in detail in [Section 3](#). The research findings provide crucial theoretical support for designing development methods for natural edge-bottom water-oil reservoirs with inclination.

2 Mathematical Model

The CO₂ huff-and-puff mechanism is complex, involving multiphase flow, phase behavior, CO₂ dissolution, and CO₂ diffusion. Therefore, the mathematical model describes the CO₂ huff-and-puff and fluid flow in pour media. It includes equations of state, basic differential equations and auxiliary equations.

2.1 Equation of State

The equation of state is widely used in phase calculations of oil and gas systems. Therefore, the PR equation of state is selected to simulate the oil and gas phase equilibrium in this paper [21,22]. For the multi-component mixed system, it is of the form

$$P = \frac{RT}{V - b_m} - \frac{a_m(T)}{V(V - b_m) + V(V + b_m)} \quad m = g, o \quad (1)$$

where R is the gas constant, taken as $8.206 \text{ J} \cdot \text{K}^{-1} \cdot \text{mol}^{-1}$; T is the temperature of the system, K; P is the pressure of the system, Pa; V is the molar volume of the system, L/mol. The equation takes into account the effects of molecular density and temperature on the intermolecular gravitational force, and a_m and b_m are the average gravitational and repulsive constants of the mixed system, respectively, with the expressions:

$$a_o(T) = \sum_{i=1}^n \sum_{j=1}^n x_i x_j (a_i a_j)^{0.5} (1 - k_{ij}) \quad (2)$$

$$a_g(T) = \sum_{i=1}^n \sum_{j=1}^n y_i y_j (a_i a_j)^{0.5} (1 - k_{ij}) \quad (3)$$

where a_i is the gravitational constant of component i ; b_i is the van der Waals co-volume of component i ; x_i is the composition of component i in the equilibrium mixed liquid phase; y_i is the composition of component i in the equilibrium mixed gas phase; k_{ij} is the binary interaction coefficient, which can be obtained by phase fitting; n is the number of components in the hydrocarbon system of oil and gas.

The cubic equation of the compression factor Z of the state equation can be expressed by [Eq. \(4\)](#):

$$Z_m^3 - Z_m^2(1 - B_m) + (A_m - 2B_m - 3B_m^2)Z_m - (A_mB_m - B_m^2 - B_m^3) = 0 \quad (4)$$

where Z_m is the compression factor of the mixture; A_m and B_m are the compression coefficients, $A_m = \frac{a_m(T)P}{(RT)^2}$ and $B_m = \frac{b_m P}{RT}$.

The fugacity coefficient of component i in a mixture can be calculated from the following equation

$$\ln\left(\frac{f_i}{x_i P}\right) = \frac{b_i}{b_m} (Z_m - 1) - \ln(Z_m - B_m) - \frac{A_m}{2\sqrt{2}B_m} \left(\frac{2\varphi_i}{a_m} - \frac{b_i}{b_m}\right) \ln\left(\frac{Z_m + 2.414B_m}{Z_m - 0.414B_m}\right) \quad (5)$$

where f_i is the fugacity coefficient of component i , which can be calculated according to the following equation:

$$\varphi_i = \sum_{j=1}^n x_j (a_i a_j)^{0.5} (1 - k_{ij}) \quad (6)$$

2.2 Basic Differential Equation (BDE)

2.2.1 Hypothetical Condition

In this paper, the multi-phase multi-component model is used to establish the mathematical model of CO₂ huff-and-puff, which can better reflect the CO₂ huff-and-puff mechanism and can accurately describe the process of CO₂-oil interaction. The basic assumptions are as follows:

- (1) The fluid flow obeys Darcy's law and the seepage process is isothermal;
- (2) There are oil, gas and water phases in the reservoir, and the water component and various hydrocarbon components are considered. The water component exists only in the water phase, the hydrocarbon component can exist in both oil and gas phases, and CO₂ exists in the hydrocarbon component.
- (3) Fluid and rock are compressible, and the effects of gravity and capillary force are considered;
- (4) The transfer of components between phases is considered, the diffusion behavior is not considered.

2.2.2 Differential Equations for Seepage

Combined with Darcy's law, the hydrocarbon component seepage equation is

$$\frac{\partial}{\partial t} [\phi z_i (S_o \rho_o + S_g \rho_g)] - \nabla \cdot \left[\frac{KK_{ro}}{\mu_o} \rho_o x_i \nabla (P_o - \rho_o g D) + \frac{KK_{rg}}{\mu_g} \rho_g y_i \nabla (P_g - \rho_g g D) \right] + q_i = 0 \quad (7)$$

The water component seepage equation is

$$\frac{\partial}{\partial t} (\phi \rho_w S_w) - \nabla \cdot \left[K \frac{K_{rw} \rho_w}{\mu_w} \nabla (P_w - \rho_w g D) \right] + q_w = 0 \quad (8)$$

where z_i is the total composition of component i ($i = 1, \dots, n$); x_i is the composition of component i in the oil phase; y_i is the composition of component i in the gas phase; S_o is oil phase saturation; S_g is gas phase saturation; ρ_o is oil phase density, kg·m⁻³; ρ_g is gas phase density, kg·m⁻³; ρ_w is aqueous phase density, kg·m⁻³; K is the absolute permeability of the reservoir, m²; K_{ro} is the relative permeability of the oil phase; K_{rg} is the relative permeability of the gas phase; K_{rw} is the relative permeability of the water phase; P_o is the pressure of the oil phase, Pa; P_g is the pressure of the gas phase, Pa; P_w is the pressure of the water phase, Pa; D is the depth, m; g is the acceleration of gravity, and 9.8 m·s⁻²; μ_o is the viscosity of the oil phase, Pa·s; μ_g is the viscosity of the gas phase, Pa·s; μ_w is the viscosity of the water phase, Pa·s; and q_i is the source term of component i , kg·s⁻¹.

The oil phase density is expressed as

$$\rho_o = \frac{P \left(\sum_{i=1}^n M_i x_i \right)}{Z_o R T} \quad (9)$$

where M_i is the molar mass of component i , kg/mol; Z_o is the compression factor of the oil phase, and is the minimum root of the cubic equation of the compression factor.

The gas phase density is

$$\rho_g = \frac{P \left(\sum_{i=1}^n M_i y_i \right)}{Z_g R T} \quad (10)$$

The aqueous phase density is

$$\rho_w = \rho_{w0} \cdot e^{(C_w(P-P_0))} \quad (11)$$

where C_w is the compression coefficient of water, Pa^{-1} ; P_0 is the reference pressure, Pa; and ρ_{w0} is the density of water at the reference condition, $\text{kg}\cdot\text{m}^{-3}$. The oil and gas phase viscosities in the component equations were calculated by using the method proposed by Jossi.

2.2.3 Auxiliary Equation

To ensure that the basic differential equation is solvable, the following equations are required

(1) Equilibrium equation

$$z_i = Lx_i + (1 - L) y_i \quad (i = 1, 2, \dots, n) \quad (12)$$

$$L = \frac{\rho_o S_o}{\rho_o S_o + \rho_g S_g} \quad (13)$$

$$k_i = \frac{y_i}{x_i} \quad (i = 1, 2, \dots, n) \quad (14)$$

where L is the mass fraction of the liquid phase in the mixture; k_i is the equilibrium constant of component i .

(2) Saturation equation

$$S_o + S_g + S_w = 1.0 \quad (15)$$

(3) Capillary pressure equation

$$\begin{aligned} P_{\text{cow}} &= P_o - P_w \\ P_{\text{cgo}} &= P_g - P_o \end{aligned} \quad (16)$$

where P_{cow} is the capillary pressure between oil and water, Pa; P_{cgo} is the capillary pressure between gas and water, Pa.

(4) Component molar fraction equations

$$\sum_{i=1}^n x_i = \sum_{i=1}^n y_i = \sum_{i=1}^n z_i = 1 \quad (17)$$

The above equations represent the mathematical model of the compositional model, employing the finite difference method for discrete equation solving. The solution is shown in [Fig. 1](#). The solution procedure is as follows:

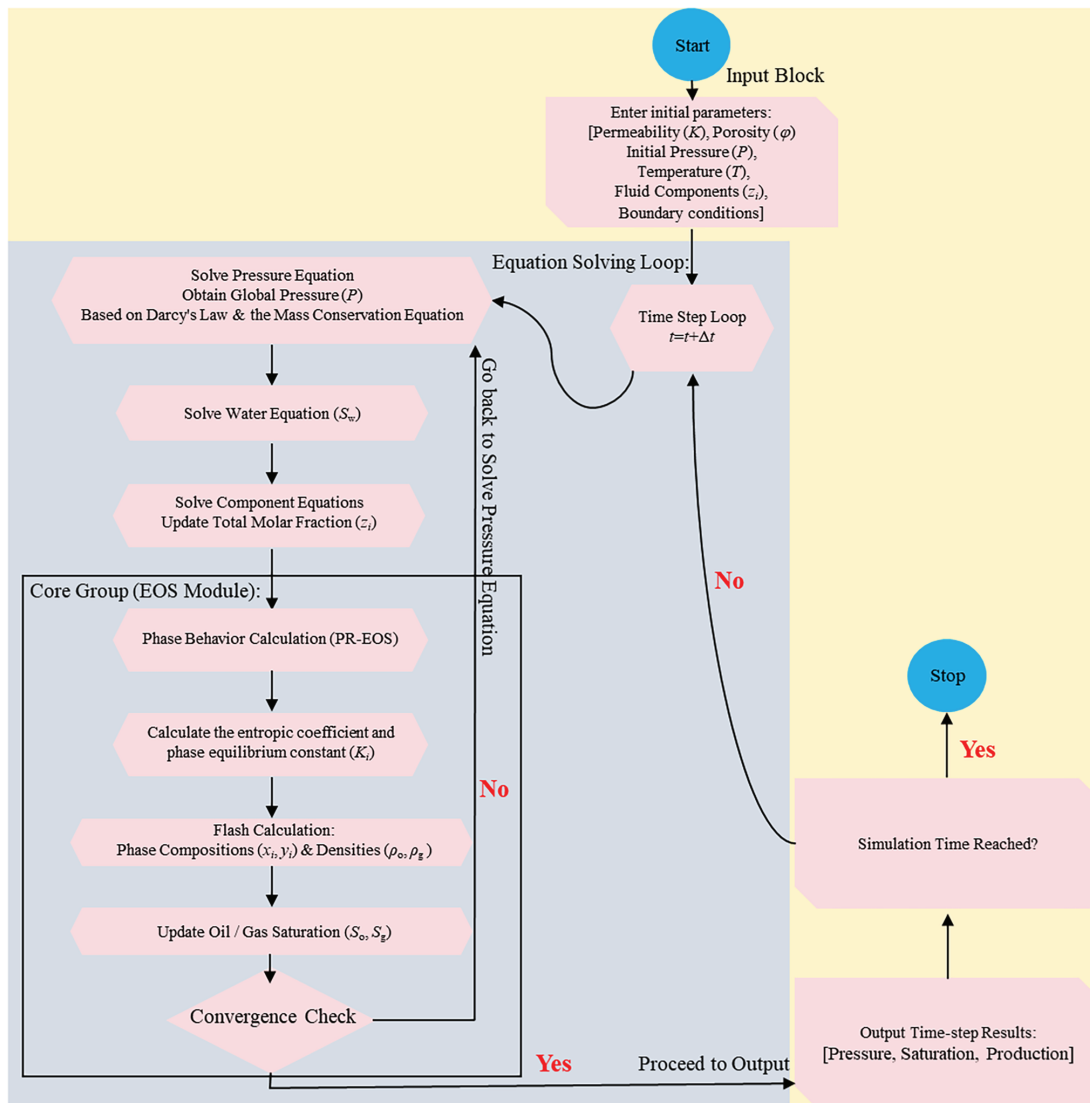


Figure 1: Flowchart of PR-EOS-based multiphase flow simulation in reservoirs

(1) Given reservoir parameters such as permeability (K), porosity (ϕ), initial pressure (P), temperature (T), etc., component properties including the composition of the oil phase (x_i) and gas phase (y_i), as well as boundary conditions, initial saturation distribution of the oil phase (S_o), gas phase (S_g), and water phase (S_w), and the initial pressure field.

(2) Time stepping involves solving the equations for each component to determine the pressure at the current time step. Subsequently, water saturation is computed using the water component equation, followed by calculating the total composition of the current time step by integrating the fundamental hydrocarbon component differential equation.

(3) Phase equilibrium calculations involve utilizing the determined pressure and overall composition to derive the composition of oil-gas two-phase flow, as well as the density, viscosity, and oil-gas saturation. Subsequent iterations are conducted by revisiting step (2).

3 Numerical Model

The NP oilfield is located in the NP depression in the northern part of the Huanghua depression in the Bohai Bay Basin, which has a complex geologic structure and consists mainly of fault-controlled fault block formations. The field contains a number of study blocks (NP-G, NP-M, etc.) due to the development of faults in the reservoir, closed small fault blocks with insufficient energy supply (NP-M) have been formed locally, different fault blocks in the reservoir have different dip angle development ($2^{\circ} \sim 40^{\circ}$), the edge water of the blocks is developed, and bottom water is also developed in some areas. The upper part of the study block is a conventional heavy oil group, with crude oil viscosity ranging from 130.4 to 229.1 mPa·s, and the lower part develops a conventional light oil group, with an average crude oil viscosity of 2.76 mPa·s. The NP-G block was put into production with a natural water flooding then CO_2 huff-and-puff was adopted, and CO_2 huff-and-puff has been implemented in 65 wells so far. Based on the positive rhythmic features of geological evolution in Block NP-G, a conceptual model with a model dip angle of 2° is developed. The oil column heights in high, middle, and low positions are 10, 7, and 1.5 m, respectively. Based on an actual reservoir block, the conceptual model incorporates an edge water feature at the low position, set at 50 times the water body multiple. In Fig. 2. for attribute characteristics. In the numerical simulation process, the actual $1 \text{ m}^3/\text{d}$ production in the oilfield is used as the criterion for the failure of huff-and-puff cycles for the next cycle of CO_2 huff-and-puff. Fig. 3 presents a comparison of multiphase flow parameters for heavy oil and light oil. Fig. 3a shows the relative permeability for heavy oil, Fig. 3b shows the relative permeability for light oil.

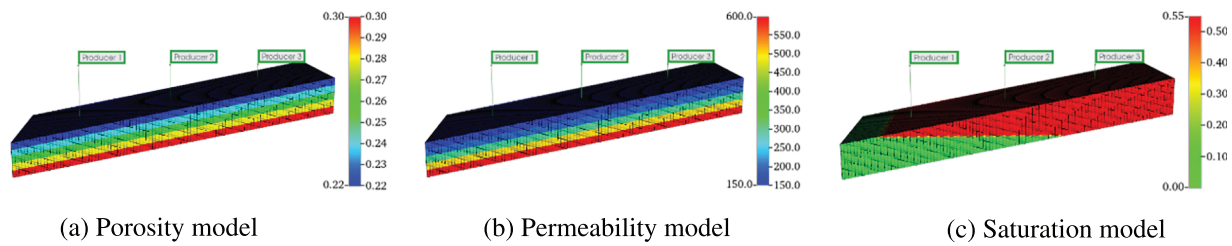


Figure 2: Conceptual model

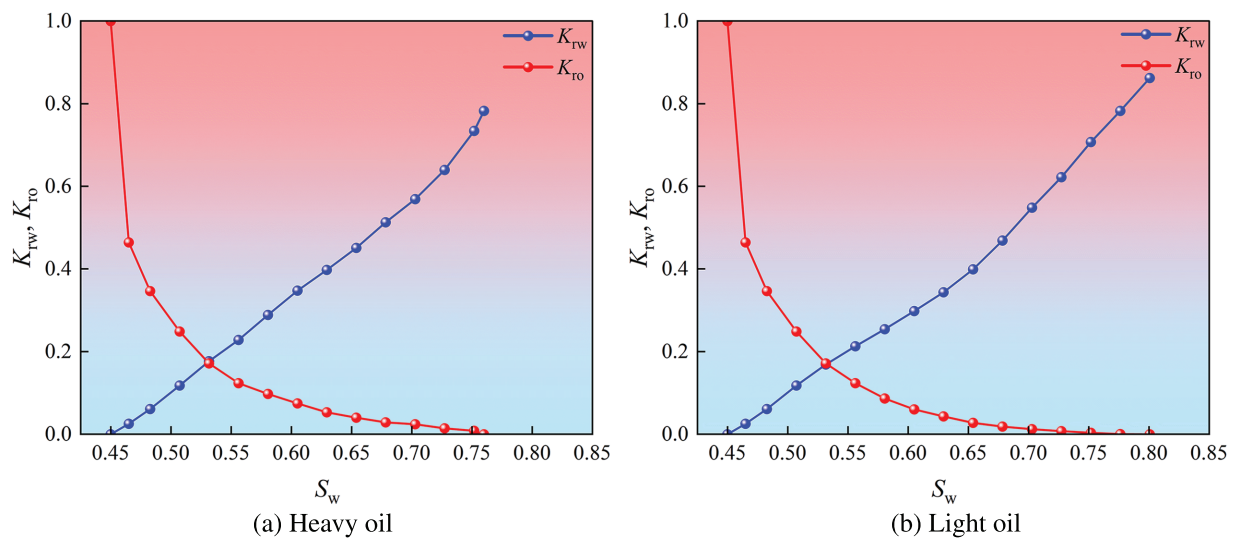


Figure 3: Relative permeability curve (heavy oil and light oil)

3.1 CO₂ Huff-and-Puff Radius on Heavy Oil and Light Oil

There are the mechanisms of dissolution, volume expansion and viscosity reduction when CO₂ interacts with crude oil in the formation. For this reason, CO₂ swept area in the formation is directly related to the effect of CO₂ huff-and-puff. Therefore, the natural edge water energy is firstly utilized for water flooding in this study, and CO₂ huff-and-puff is conducted when the water cut is 95%, and after selecting the CO₂ swept area, the average oil saturation of the swept area is calculated, as shown in Fig. 4. Based on the numerical simulation results, the swept radius and swept area after CO₂ huff-and-puff remain basically unchanged for 10 cycles of heavy oil and 9 cycles of light oil. Figs. 5 and 6 show the swept radius, swept area and oil saturation, respectively. It can be seen that with the increase of CO₂ huff-and-puff cycles, the CO₂ swept area gradually increased. After 10 cycles of CO₂ huff-and-puff, the maximum CO₂ swept radius in heavy oil is 100 m, and the swept area is 19,171.9 m³; After 8 cycles of CO₂ huff-and-puff, the maximum CO₂ swept radius in light oil is 65 m, and the swept area is 13,273.2 m³. From the variation of the four maximum sweep radius and the CO₂ swept area, it can be seen that the increase of CO₂ swept radius becomes smaller obviously when the seventh cycle injection is conducted. According to average oil saturation of the swept area, the reduction of the average oil saturation also significantly declines after the seventh cycle of CO₂ huff-and-puff, indicating that the effect of CO₂ huff-and-puff is also gradually deteriorating. The average oil saturation change over 10 cycles is calculated, the average oil saturation reduces by 0.8%–1.9% per cycle. Compared with Fig. 6, the maximum sweep radius and oil saturation in light oil shows that CO₂ huff-and-puff shows superior performance in heavy oil reservoirs compared to light oil. This is primarily due to the high viscosity and poor mobility of heavy oil, and the rapid coning of edge-bottom water for heavy oil results in low oil recovery during water flooding. Residual oil saturation is high prior to the CO₂ huff-and-puff, consequently, CO₂ injection can interact with oil over a larger range, exhibiting stronger viscosity reduction and swelling effects on heavy oil. Therefore, the oil saturation reduction per cycle is more pronounced, with an average reduction in oil saturation per cycle being 0.58%, greater than that in light oil.

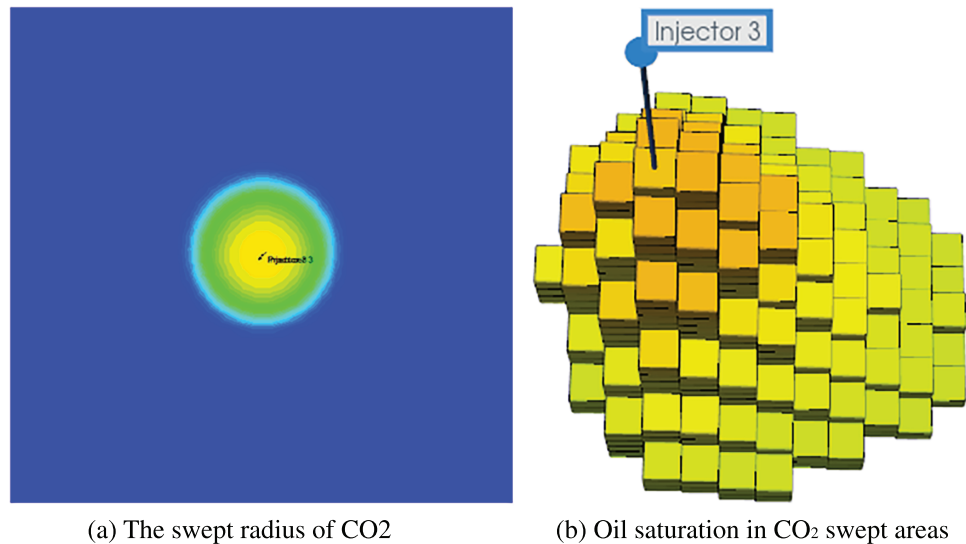


Figure 4: CO₂ huff-and-puff swept radius and average oil saturation calculation

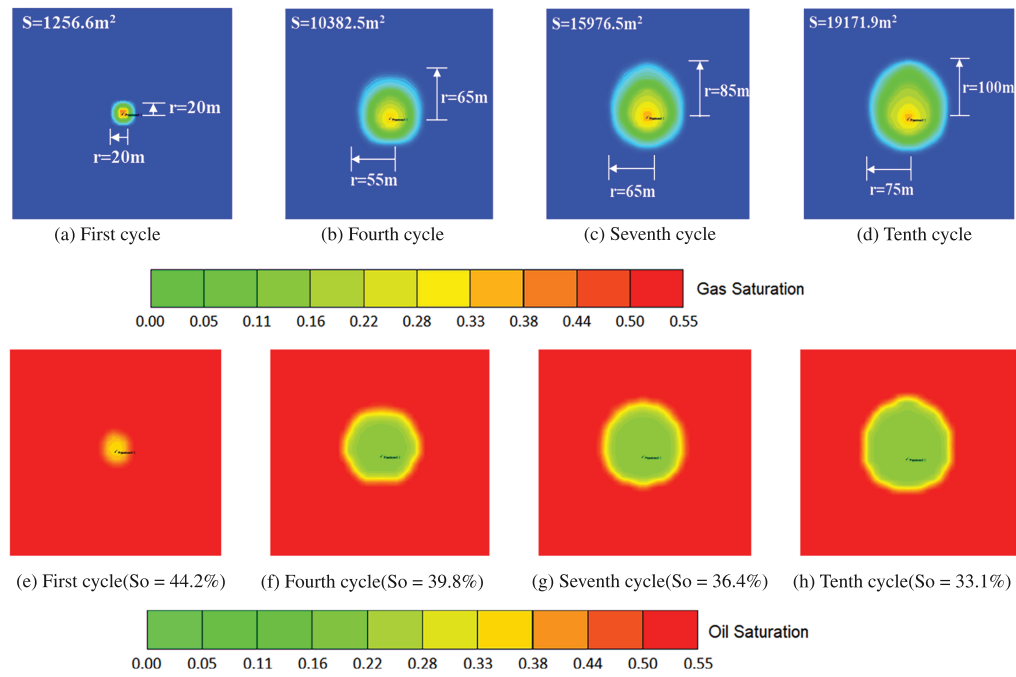


Figure 5: CO₂ huff-and-puff molar fraction and oil saturation at 10 m oil column height ($\mu = 170 \text{ mPa}\cdot\text{s}$)

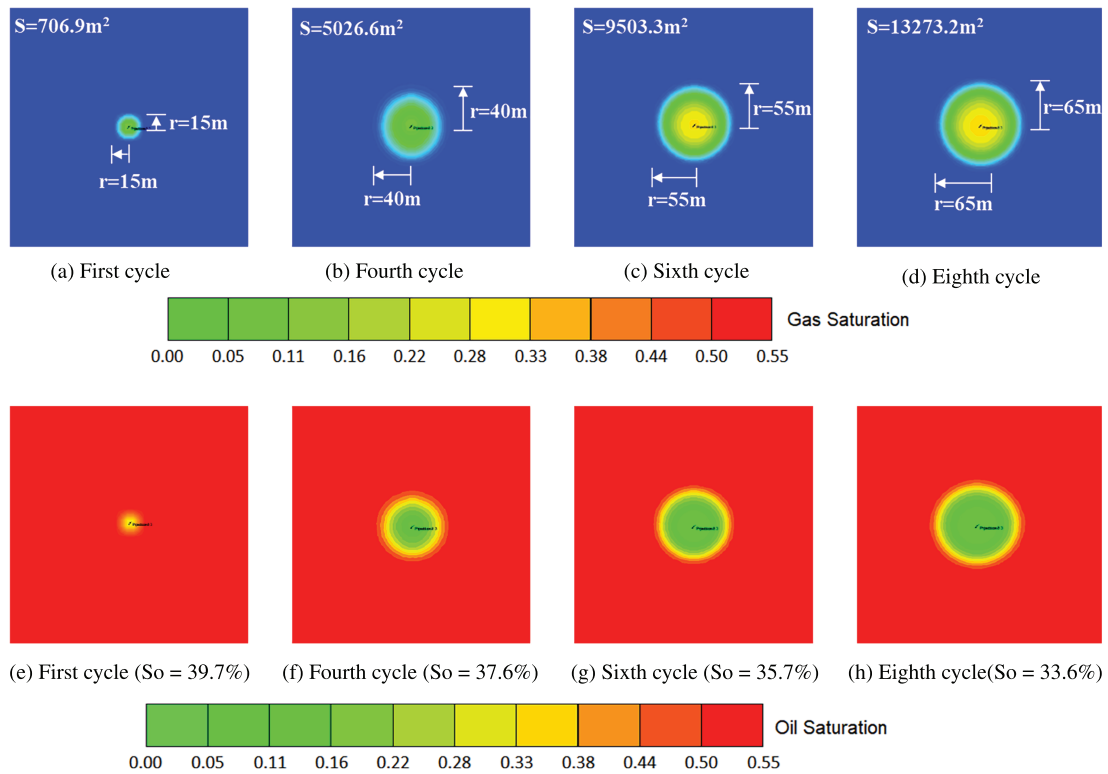


Figure 6: CO₂ huff-and-puff radius and average oil saturation at 10 m oil column height ($\mu = 2.7 \text{ mPa}\cdot\text{s}$)

Fig. 7 illustrates daily oil production in CO₂ huff-and-puff for crude oils with two different viscosities. Defining cumulative oil production of less 50 t per cycle as the criterion for huff-and-puff failure, the optimal CO₂ huff-and-puff cycles for heavy oil are 9 with a cumulative oil production of 2550 t, while for light oil, the optimal cycles are 7 with a cumulative production of 1790 t. The daily oil production curve indicates that the CO₂ huff-and-puff performance of crude oils with two different viscosities sharply declines from the fourth cycle onward. This is due to the reduced increase in the CO₂ swept radius and swept area after the fourth cycle.

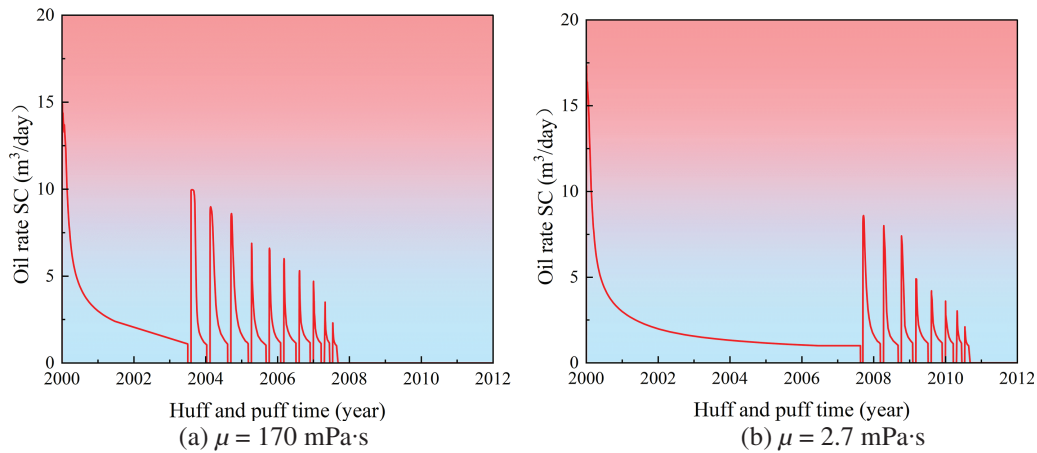


Figure 7: The daily oil production of different cycles for wells with different viscosities and 10 m oil column height

3.2 Adaptability of CO₂ Huff-and-Puff to Heavy and Light Oil

Fig. 8 presents the oil production and oil exchange ratio (oil production/gas injection volume) during CO₂ huff-and-puff cycles. The results are for oils of different viscosities with constant oil column heights. The results demonstrate that the cumulative heavy oil production and oil exchange ratio is greater than that of light oil. This comparison is made under the same gas injection volumes, soaking times, and injection rates.

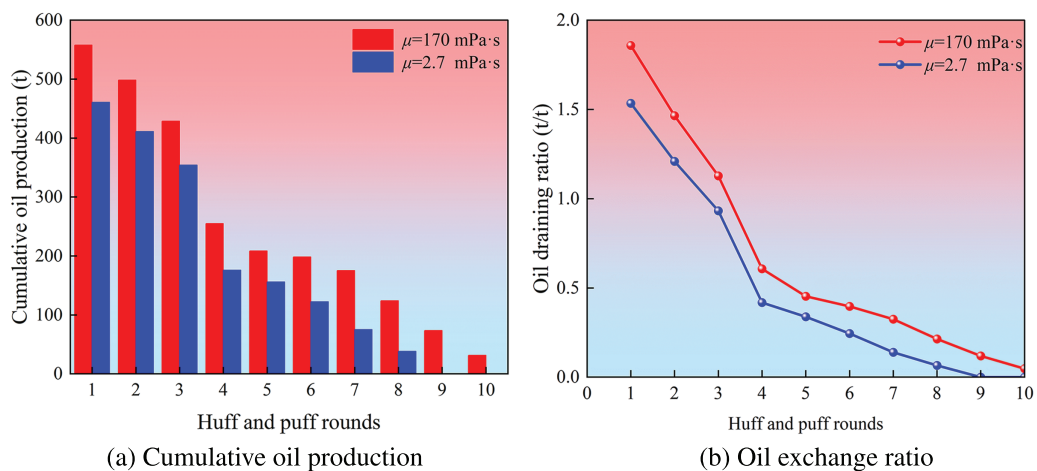


Figure 8: CO₂ huff-and-puff development effect in oil wells with oil viscosities and 10 m oil column heights

In the actual development of shallow NP reservoirs, the wells in the medium and high sections of heavy oil groups are regarded as Type I well, while the wells in the high sections of light oil groups and the low

sections of heavy oil groups are regarded as Type II well. According to the actual well production, the oil exchange ratio and the cost-to-benefit ratio variations of CO₂ huff-and-puff are calculated, as shown in Fig. 9. The cost-to-benefit ratio is defined as the total output revenue divided by the total input cost, with the oil price set at 444.15 \$/t. Excluding fixed costs, the CO₂ huff-and-puff cost is 63.09 \$/t and the oil and gas production operating cost is 144.41 \$/t.

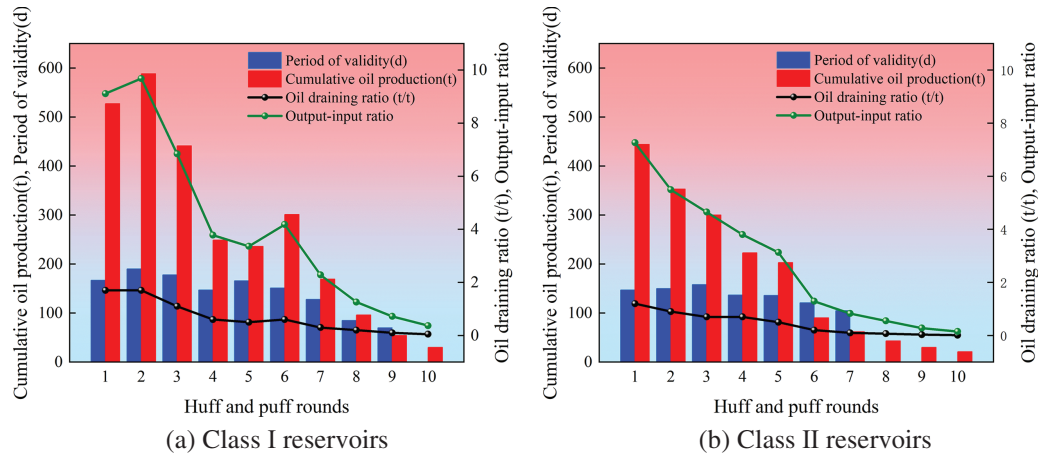


Figure 9: Statistical diagram of the implementation effect of NP shallow reservoirs

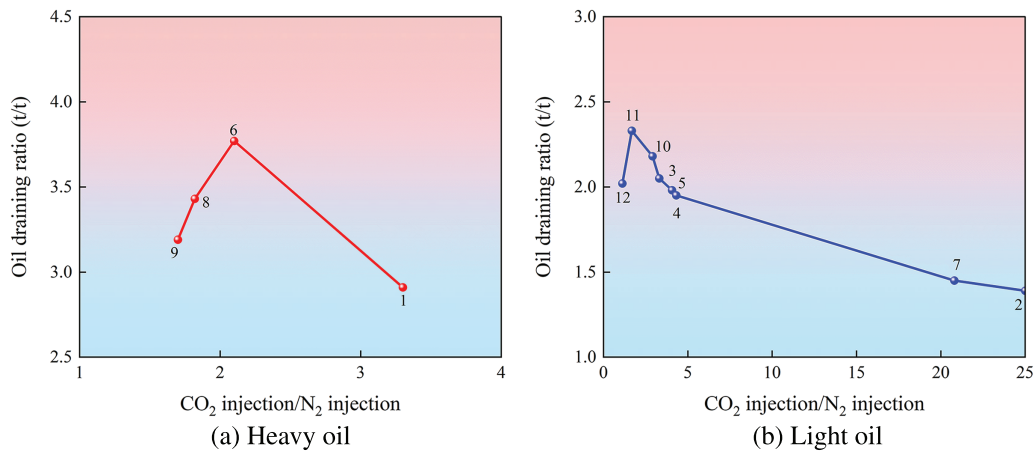
As shown in Fig. 9, the average single-well oil production for Type I well is 359 t per cycle, while that for Type II well is 239 t per cycle. This study determined the optimal CO₂ huff-and-puff cycles and the corresponding oil production per cycle for wells with a 10 m oil column height. The results are consistent with actual field development results. Therefore, the results of this study can provide important theoretical support for CO₂ field practice in similar reservoirs.

3.3 Adaptability of CO₂ and N₂ Synergistic Huff-and-Puff to Heavy Oil and Light Oil

During the development of the NP-M block, the development of reservoir faults has led to the formation of small fault-block areas with poor energy supply locally. Considering that the reservoir has a dip angle, the gravity override of N₂ is utilized in actual development, and the CO₂ and N₂ synergistic huff-and-puff is implemented. However, the adaptability to CO₂ and N₂ synergistic huff-and-puff technology to the oils of different viscosities, especially the optimal injection ratio of CO₂ and N₂, still lacks of in-depth understanding. Therefore, to accommodate the geological and dip characteristics of the NP-M block, the reservoir dip angle is set as 10°. The small-energy bottom water of 10 times the reservoir pore volume at the low part of the model is set. This study focuses merely on the development performance of production wells in the middle section. The wells are produced at the constant liquid rate of 10 m³/d until the oil production declines to 2 m³/d under depletion development, and the N₂ and CO₂ synergistic huff-and-puff is initiated, the development performance is calculated for the heavy oil and light oil. The injection volumes of N₂ are 1 × 10⁴ m³, 5 × 10⁴ m³, 8 × 10⁴ m³, 10 × 10⁴ m³, and 15 × 10⁴ m³, while the injection volumes of CO₂ are 200, 250, 300, 350, and 400 t. This study employs an orthogonal design method to formulate the simulation scheme, comprising a total of 12 schemes (as shown in Table 1). The optimal gas injection ratio is determined by comparing the oil exchange ratio of different schemes, and the simulation results as illustrated in Fig. 10.

Table 1: Simulation schemes

Scheme	N ₂ (10 ⁴ m ³)	N ₂ (t)	CO ₂ (t)	Viscosity (mPa·s)
1	5	60	200	170
2	1	12	300	2.7
3	10	120	400	2.7
4	5	60	250	2.7
5	8	96	400	2.7
6	8	96	200	170
7	1	12	250	2.7
8	15	180	350	170
9	15	180	300	170
10	10	120	350	2.7
11	15	180	300	2.7
12	15	180	200	2.7

**Figure 10:** Relationship curve between the ratio of oil draining rate and gas injection volume

As shown in the figure, with the decrease of the injection ratio (the increase of N₂ injection volume), the oil exchange ratio of heavy oil and light oil initially increase and then decrease. This trend is primarily attributed to the fact that when the N₂ injection volume is low, the gravity override is not significant in Fig. 11a. As the N₂ injection volume increases, the gravity override effect becomes more pronounced, which leads to the higher displacement efficiency of residual oil in the upper zones (Fig. 11b). However, with increase of N₂ injection volume, gas channeling occurs, which results in the formation of residual oil enrichment zones and the decline in oil displacement efficiency (Fig. 11c). Therefore, the oil exchange ratio is used as the evaluation criterion, and the inflection point of the gas injection ratio curve is taken as the optimal injection ratio. The optimal CO₂: N₂ injection ratio for heavy oil is 2.1, and the maximum oil exchange ratio is 3.77 t/t. For light oil, the optimal injection CO₂:N₂ ratio is 1.67, and the maximum oil exchange ratio is 2.33 t/t. The difference primarily arises from the higher viscosity of heavy oil compared to the light oil, and the greater CO₂ injection volume, the more effectively viscosity reduction.

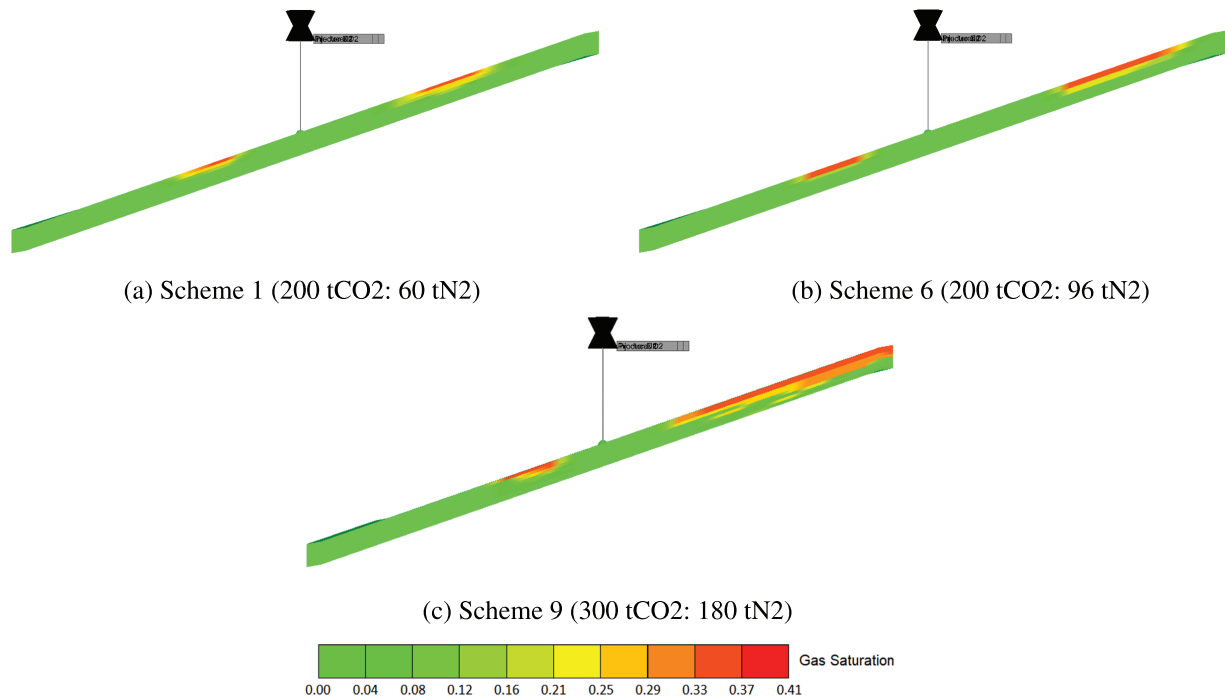


Figure 11: Gas saturation distribution of heavy oil under CO₂ and N₂ synergistic huff-and-puff

To further study the energy enhancement and supplement effects of N₂, Fig. 12 presents the formation pressure under different injection schemes. It can be observed that the higher N₂ injection volume leads to the greater increase in formation pressure under the same viscosity conditions, which indicates the more pronounced energy enhancement effect of N₂. When the appropriate volume of N₂ is injected, it can effectively enhance the gravity override effect of N₂, thereby tapping into the residual oil in the upper reservoir zones and improving oil recovery. The reason is that N₂ is a highly expansive gas. When the N₂ is injected into the formation, as the injection volume increases, N₂ that does not dissolve in the oil occupies the formation pore and fracture space. With the swelling of N₂, the formation pressure gradually increases.

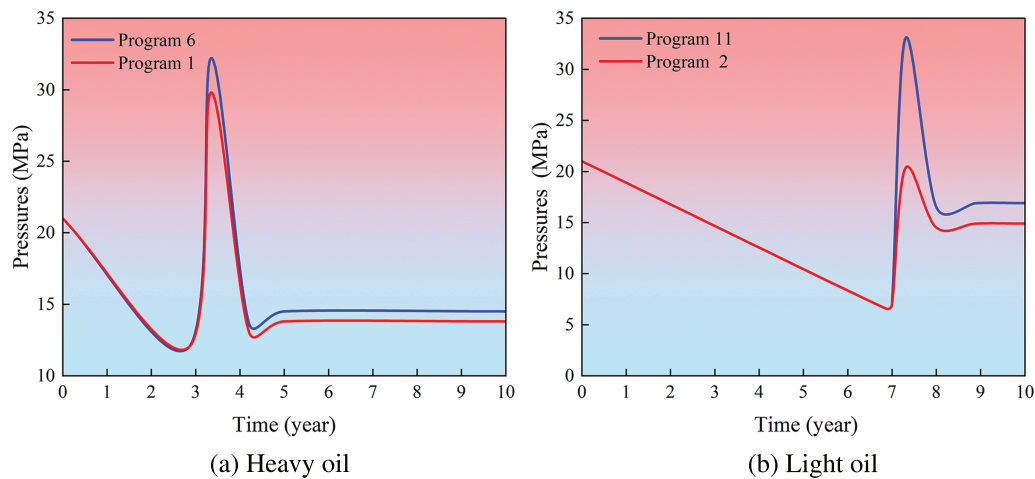


Figure 12: Formation pressure under different injection schemes

4 Conclusions

(1) CO₂ huff-and-puff shows superior performance in heavy oil reservoirs compared to light oil. After 10 cycles of CO₂ huff-and-puff, the maximum sweep radius in heavy oil reaches 100 m, the average oil saturation reduction by 0.8%–1.9% per cycle. The maximum sweep radius in light oil merely reaches 65 m, the average oil saturation reduction in light oil per cycle is 0.58% lower than in heavy oil.

(2) The daily oil production of CO₂ huff-and-puff sharply declined in the fourth cycle. The optimal CO₂ huff-and-puff cycles were 9 for heavy oil groups, with the cumulative oil production of 2550 t. The optimal CO₂ huff-and-puff cycles were 7 for light oil groups, with a cumulative oil production of 1790 t.

(3) For oil wells with insufficient energy supply, CO₂ and N₂ synergistic huff-and-puff is employed to improve oil displacement efficiency. With increase of N₂ injection volume, the gravity override effect of N₂ improve oil recovery. However, further increasing the N₂ injection volume may lead to gas channeling, which adversely affects development performance. The optimal CO₂: N₂ injection ratio for heavy oil is 2.1:1, achieving the maximum oil exchange ratio (3.77). For light oil, the optimal ratio is 1.67:1, achieving the highest oil exchange ratio (2.33).

Although the above results provide supporting evidence for the application of CO₂ and CO₂:N₂ synergistic huff-and-puff technology in NP reservoirs, this study still has certain limitations. Specifically, the constructed numerical model has not yet incorporated the geochemical reactions among CO₂, formation water, and rock. Future research will expand this model to include more influencing factors, thereby further validating and optimizing the technical approach proposed in this work.

Acknowledgement: None.

Funding Statement: The work presented in this study was financially supported by the National Natural Science Foundation of China (Grant No. 52374032) and the Key Research and Development Program of Heilongjiang Province (Grant No. JD22A004).

Author Contributions: The authors confirm contribution to the paper as follows: Writing, analysis and interpretation of results, preparation of the draft: Xiutai Cao; Review resources and methodology guidance: Huiying Zhong; Editing and writing: Yuxin Sun and Bowen Shi; Data collection, conception: Hao Zhang and Hongli Tang; Supervision: Yongbin Bi. All authors reviewed the results and approved the final version of the manuscript.

Availability of Data and Materials: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Ethics Approval: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest to report regarding the present study.

References

1. Zhou X, Yuan Q, Peng X, Zeng F, Zhang L. A critical review of the CO₂ huff ‘n’ puff process for enhanced heavy oil recovery. *Fuel*. 2018;215(2):813–24. doi:10.1016/j.fuel.2017.11.092.
2. Liu J, Li H, Tan Q, Liu S, Zhao H, Wang Z. Quantitative study of CO₂ huff-n-puff enhanced oil recovery in tight formation using online NMR technology. *J Petrol Sci Eng*. 2022;216(3):110688. doi:10.1016/j.petrol.2022.110688.
3. Abedini A, Torabi F. Oil recovery performance of immiscible and miscible CO₂ huff-and-puff processes. *Energy Fuels*. 2014;28(2):774–84. doi:10.1021/ef401363b.
4. Rogelj J, den Elzen M, Höhne N, Fransen T, Fekete H, Winkler H, et al. *Paris agreement climate proposals need a boost to keep warming well below 2°C*. *Nature*. 2016;534(7609):631–9. doi:10.1038/nature18307.

5. Lei Z, Liu Y, Wang R, Li L, Liu Y, Zhang Y. A microfluidic experiment on CO₂ injection for enhanced oil recovery in a shale oil reservoir with high temperature and pressure. *Energies*. 2022;15(24):9461. doi:10.3390/en15249461.
6. Zhou X, Li X, Shen D, Shi L, Zhang Z, Sun X, et al. CO₂ huff-n-puff process to enhance heavy oil recovery and CO₂ storage: an integration study. *Energy*. 2022;239:122003. doi:10.1016/j.energy.2021.122003.
7. Ampomah W, Balch RS, Grigg RB, McPherson B, Will RA, Lee SY, et al. Co-optimization of CO₂-EOR and storage processes in mature oil reservoirs. *Greenhouse Gases*. 2017;7(1):128–42. doi:10.1002/ghg.1618.
8. Peng X, Wang Y, Diao Y, Zhang L, Yazid IM, Ren S. Experimental investigation on the operation parameters of carbon dioxide huff-n-puff process in ultra low permeability oil reservoirs. *J Petrol Sci Eng*. 2019;174(43):903–12. doi:10.1016/j.petrol.2018.11.073.
9. Li S, Lu C, Wu M, Hu Z, Li Z, Wang Z. New insight into CO₂ huff-n-puff process for extraheavy oil recovery via viscosity reducer agents: an experimental study. *J CO₂ Util*. 2020;42(9):101312. doi:10.1016/j.jcou.2020.101312.
10. Xu J, Wan H, Wu Y, Liu S, Yan B. Study on CO₂-enhanced oil recovery and storage in near-depleted edge-bottom water reservoirs. *J Mar Sci Eng*. 2024;12(11):2065. doi:10.3390/jmse12112065.
11. Dou LR, Sun LD, Lyu WF, Wang MY, Gao F, Gao M, et al. Trend of global carbon dioxide capture, utilization and storage industry and challenges and countermeasures in China. *Petrol Explor Dev*. 2023;50(5):1083–96. (In Chinese). doi:10.1016/s1876-3804(23)60463-x.
12. Zhang L, Zhang T, Leng J, Zheng Z, Qi Y, Tang L, et al. Comprehensive numerical Evaluation of CO₂ huff-n-puff in an offshore tight oil reservoir: a case study in Bohai Bay Area. *ACS Omega*. 2024;9(22):23892–23902. doi:10.1021/acsomega.4c01907.
13. Liu J, Xie M, Liu D, Cao L, Xie S, Chang Y, et al. Research on mechanism and effect of enhancing gas recovery by CO₂ huff-n-puff in shale gas reservoir. *ACS Omega*. 2024;9(30):33111–33118. doi:10.1021/acsomega.4c04464.
14. Xu Z, Zhou L, Ma S, Qin J, Huang X, Han B, et al. Study on CO₂ huff-n-puff development rule of horizontal wells in heavy oil reservoir by taking Liuguangzhuang oilfield in dagang as an example. *Energies*. 2023;16(11):4258. doi:10.3390/en16114258.
15. Zhao F, Wang Y, Huang S, Liu M, Yang C. Implementation and adaptability analysis of numerical simulation for shale oil CO₂ huff and puff. *Energies*. 2024;17(2):454. doi:10.3390/en17020454.
16. Shabib-Asl A, Chen SN, Zheng S. Performance of CO₂ foam huff and puff in tight oil reservoirs. *Front Energy Res*. 2022;10:826469. doi:10.3389/fenrg.2022.826469.
17. Afari S, Ling K, Sennaoui B, Maxey D, Oguntade T, Porlles J. Optimization of CO₂ huff-n-puff EOR in the Bakken Formation using numerical simulation and response surface methodology. *J Petrol Sci Eng*. 2022;215(4):110552. doi:10.1016/j.petrol.2022.110552.
18. Wei M, Bai B. Effect of molecular-diffusion mechanism on CO₂ Huff-n-puff process in shale-oil reservoirs. In: *Proceedings of the Society of Petroleum Engineers-SPE Kingdom of Saudi Arabia Annual Technical Symposium and Exhibition; 2017 Apr 27; Dammam, Saudi Arabia*. p. 582–8. doi:10.2118/188003-MS.
19. Tang X, Li YQ, Han X, Zhou YB, Zhan JF, Xu MM, et al. Dynamic characteristics and influencing factors of CO₂ huff and puff in tight oil reservoirs. *Petrol Explor Dev*. 2021;48(4):817–24. (In Chinese). doi:10.1016/s1876-3804(21)60079-4.
20. Wang P, Zhao F, Huang S, Zhang M, Feng H, Li Y, et al. Laboratory investigation on oil increment and water cut control of CO₂, N₂, and gas mixture huff-n-puff in edge-water fault-block reservoirs. *J Energy Resour Technol*. 2021;143(8):083001. doi:10.1115/1.4048862.
21. Soave G. Equilibrium constants from a modified Redlich-Kwong equation of state. *Chem Eng Sci*. 1972;27(6):1197–203. doi:10.1016/0009-2509(72)80096-4.
22. Peng DY, Robinson DB. A new two-constant equation of state. *Ind Eng Chem Fund*. 1976;15(1):59–64. doi:10.1021/i160057a011.