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Sensitivity Study of CO_2 Huff-n-Puff in the X Block

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Abstract

Shale reservoirs, due to their highly compact nature, present challenges for traditional waterflooding development, as it is difficult to establish an effective displacement pressure system. This results in a rapid decline in production and low average single-well productivity, severely limiting development efficiency. Therefore, there is an urgent need to explore innovative development technologies that can quickly replenish reservoir energy and enhance recovery rates. CO_2 injection offers an effective solution to this problem. It not only helps maintain reservoir pressure but also improves reservoir properties and flow capacity by reducing oil viscosity, extracting light components from the oil, solute expansion, improving the oil-water mobility ratio, and lowering interfacial tension. This, in turn, increases the recovery factor of shale reservoirs. Based on the geological characteristics of a typical well group in the X region, this study established a heterogeneous numerical model to systematically compare and analyze the applicability of two development methods: continuous CO_2 injection and CO_2 Huff-n-Puff, in the X block. Ultimately, CO_2 Huff-n-Puff was selected as the technical pathway for enhancing recovery. Several key parameters were subjected to single-factor analysis, including the timing of Huff-n-Puff initiation, the amount of gas injected per cycle, injection rate, soaking time, and the number of Huff-n-Puff cycles. The results showed that reasonable adjustments to these parameters can significantly improve cumulative oil production and CO_2 oil recovery rate. Among these, optimizing the initiation timing, precisely controlling the injection rate, and adjusting soaking time were particularly critical for improving development outcomes.On this basis, the study conducted multi-factor parameter optimization of the CO_2 Huff-n-Puff development scheme through orthogonal experiments, and eventually proposed an optimized CO_2 Huff-n-Puff plan suitable for the X block. The results demonstrated that the optimized plan effectively enhanced production in the X oilfield. This study provides theoretical support and technical reference for the application of CO_2 Huff-n-Puff technology in shale reservoirs.

Keywords

Sensitivity, CO2 Huff-n-Puff, X Block.

1. Introduction

Shale oil, as one of the major unconventional energy sources, has become a key focus for research and development across countries. By 2040, it is expected that shale oil will still account for approximately 50% of the world's primary energy [5]. Shale oil resources are widely distributed across various regions, with significant deposits in North America, Eastern Europe, and the Asia-Pacific region. Notable countries with substantial shale oil resources include the United States, Russia, and China. By the end of 2020, China's annual shale oil production reached 311,000 tons [13]. The primary shale oil resources in China are located in the Ordos Basin, Songliao Basin, Qaidam Basin, Tarim Basin, Junggar Basin, Sichuan Basin, and Bohai Bay Basin. These regions have rich shale oil reserves with great development potential, making them the main hotspots for China's shale oil industry [8]. As of now, proven recoverable

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reserves are estimated at approximately 300-600 million tons, with a broad development outlook [9].

Due to the high density and strong heterogeneity of shale reservoirs, traditional waterflooding methods struggle to establish an effective displacement pressure system. The injection capacity of the formation is poor, and conventional gas injection often yields suboptimal results, making it difficult to effectively exploit shale oil reservoirs using conventional water and gas injection methods [15]. Shale oil reservoirs are often developed using horizontal wells and multi-stage hydraulic fracturing [12], which initially results in high production rates [19]. However, due to the lack of energy replenishment, the formation pressure declines rapidly, and daily production capacity also decreases quickly [2], leading to a low final recovery rate of only about 5-10% [10]. Therefore, additional methods are often required to enhance recovery after horizontal drilling and volumetric fracturing.

CO_2 injection technology can effectively maintain formation energy and improve reservoir properties by reducing oil viscosity, extracting light components from the oil, solute expansion, improving the oil-water mobility ratio, and lowering interfacial tension [7]. This enhances the reservoir's flow capacity and further increases the recovery factor of shale reservoirs[17].

As research into CO_2 enhanced oil recovery technology progresses, its limitations are becoming increasingly apparent [16]. Different displacement methods, such as alternating gas-water flooding, continuous gas flooding, and CO_2 Huff-n-Puff, produce varying results [14]. Even within the same displacement method, different operational parameters can significantly affect the effectiveness of CO_2 flooding. In CO_2 Huff-n-Puff operations, key parameters such as the amount of CO_2 injected, injection timing, soaking time, and the number of Huff-n-Puff cycles directly impact reservoir development outcomes and the overall efficiency of CO_2 Huff-n-Puff [19]. Therefore, determining reasonable CO_2 Huff-n-Puff operational parameters is crucial for improving oilfield recovery rates[18].

Using data from Elm Coulee, examined the effects of different injected gases (CO_2, miscible hydrocarbon gases, and immiscible hydrocarbon gases) on recovery rates [6]. Their results indicated that CO_2 and other gases had similar effects in enhancing recovery, raising recovery rates from 6% to approximately 20%. [4] using numerical simulation methods, studied the effectiveness of CO_2 Huff-n-Puff in improving recovery rates in typical Bakken shale reservoirs. The results showed that under conditions of low matrix permeability, CO_2 Huff-n-Puff improved the recovery rate by about 3.5% after three cycles compared to depletion recovery. [21] analyzed the effects of parameters such as daily CO_2 injection volume, soaking time, and the number of Huff-n-Puff cycles on recovery rates in the Bakken shale reservoir. Their findings showed that the most significant factors influencing recovery efficiency were CO_2 injection rate, soaking time, and the number of cycles, in that order. [20] using numerical simulations, studied CO_2 miscible recovery in shale reservoirs. Their results indicated that when the injected gas concentration exceeded a certain level, miscibility could be achieved even at lower pressures. Smaller fracture spacing improved the final recovery rate, and after 20 cycles of CO_2 Huff-n-Puff, oil viscosity was reduced from 0.295 cp to 0.08 cp, significantly improving recovery. [22] conducted CO_2 Huff-n-Puff experiments on the Eagle Ford shale reservoir, studying the impact of soaking time on recovery from fractured matrix-type shale oil reservoirs. The results showed that, within a certain range, the recovery rate of a single Huff-n-Puff cycle increased with longer soaking times. [1] using numerical simulations, researched the impact of CO_2 Huff-n-Puff on recovery rates in the Bakken shale reservoir. The results demonstrated that the diffusion mechanism is a key factor in final recovery rates, with CO_2 Huff-n-Puff models that considered diffusion showing a 2% higher recovery rate than those that did not. [23] compared 12 CO_2 Huff-n-Puff and continuous injection scenarios, simulating the effect of CO_2 enhanced oil recovery (EOR). They studied the impact of matrix permeability, ranging from 0.001 mD to 0.1 mD, on the performance of CO_2 Huff-n-Puff versus continuous injection. The results indicated

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that when permeability was less than 0.03 mD, CO_2 Huff-n-Puff had higher recovery rates than continuous CO_2 injection. The greatest influence on matrix permeability was fracture development, followed by well pattern and well interaction. [11] established a component numerical model incorporating hydraulic fractures for typical Chang 7 shale oil reservoirs in the Ordos Basin, evaluating CO_2 Huff-n-Puff recovery efficiency. The results showed that hydraulic fractures and natural fractures had a significant impact on CO_2 flow capacity, with the ranking of CO_2 Huff-n-Puff parameter influence as follows: number of cycles, injection rate, and soaking time. [3] conducted laboratory core experiments to study the effect of CO_2 huff-n-puff on recovery efficiency in different matrix permeability models under the development of fractures. The results showed that as the amount of CO_2 injected increased, the ultimate recovery rate improved. However, excessive CO_2 injection had a minimal effect on further enhancing the recovery rate, and cores with developed fractures had a recovery rate 14% higher than those without fractures.

These studies demonstrate that CO_2 Huff-n-Puff is an effective method for improving shale oil recovery, with significant impacts from parameters such as injection rate, soaking time, and the number of Huff-n-Puff cycles. However, there is currently a lack of systematic in-depth analysis of these influencing factors. Therefore, the primary goal of this study is to conduct a sensitivity analysis and comparison of five key factors in CO_2 Huff-n-Puff recovery: timing, cyclic gas injection volume, injection rate, soaking time, and the number of cycles, to clarify their impact on recovery and determine the optimal CO_2 Huff-n-Puff strategy.

2. Methodology

Introduction to Numerical Simulation Software. UNCONG is a multi-physics numerical simulator developed by Beijing Soft Energy Innovation Technology Co., Ltd., specifically designed for modeling fractured oil and gas reservoirs. This simulator effectively addresses complex issues encountered in the simulation of both conventional and unconventional reservoirs (such as tight oil, shale oil, shale gas, and coalbed methane) through the integration of black oil & compositional models, pipe flow models, and rock mechanics models.

UNCONG employs the Embedded Discrete Fracture Model to simulate hydraulic and natural fractures. It is widely used in various fields, including production history matching, production forecasting, completion methods and production regime optimization, and EUR evaluation. Compared to international reservoir simulators, UNCONG not only offers comprehensive functionality but also features unique characteristics. It fully implements the EDFM method and demonstrates significant advantages in terms of stability and computational efficiency.

Introduction to the Embedded Discrete Fracture Model. The Embedded Discrete Fracture Model (EDFM) is an advanced numerical method used for simulating fracture behavior in oil and gas reservoirs. EDFM embeds discrete fractures within the background grid, allowing for precise representation of complex fracture geometries without the need for excessive grid refinement. This approach enables efficient and accurate simulation of fluid flow in fractured reservoirs**.**

Simulation Workflow. To evaluate the application effect of CO_2 Huff-n-Puff in the Changqing X block, this study uses UNCONG software to perform numerical simulations of continuous CO_2 injection and CO_2 Huff-n-Puff. The workflow includes: establishing a well group numerical model, determining CO_2 injection methods, performing sensitivity analysis of CO_2 Huff-n-Puff, and providing analysis results and discussion of the optimal scheme. The specific workflow is shown in **Figure 1**.

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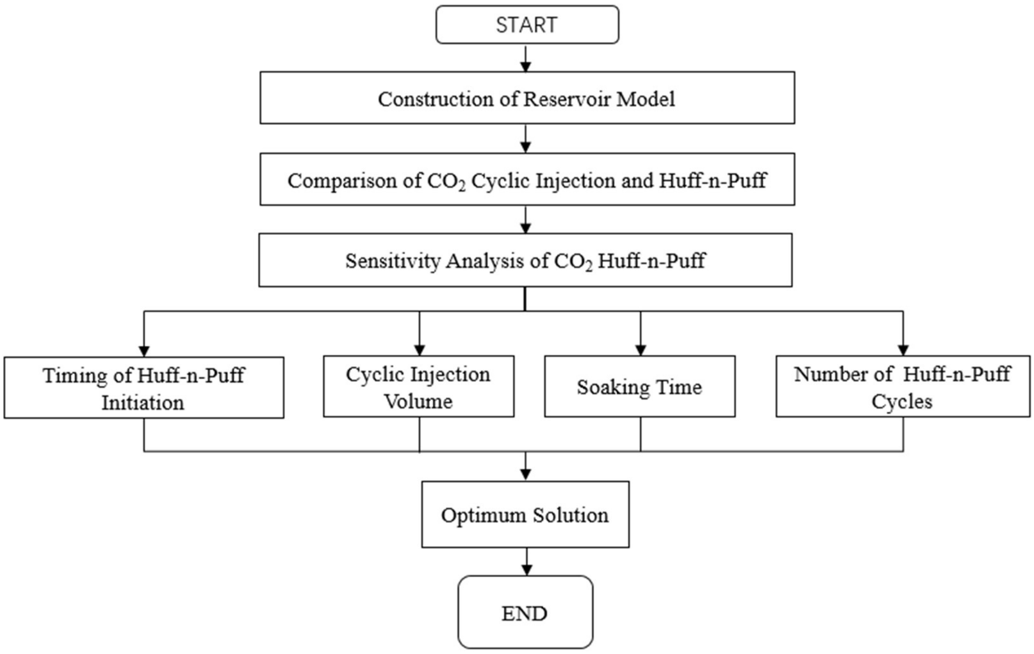
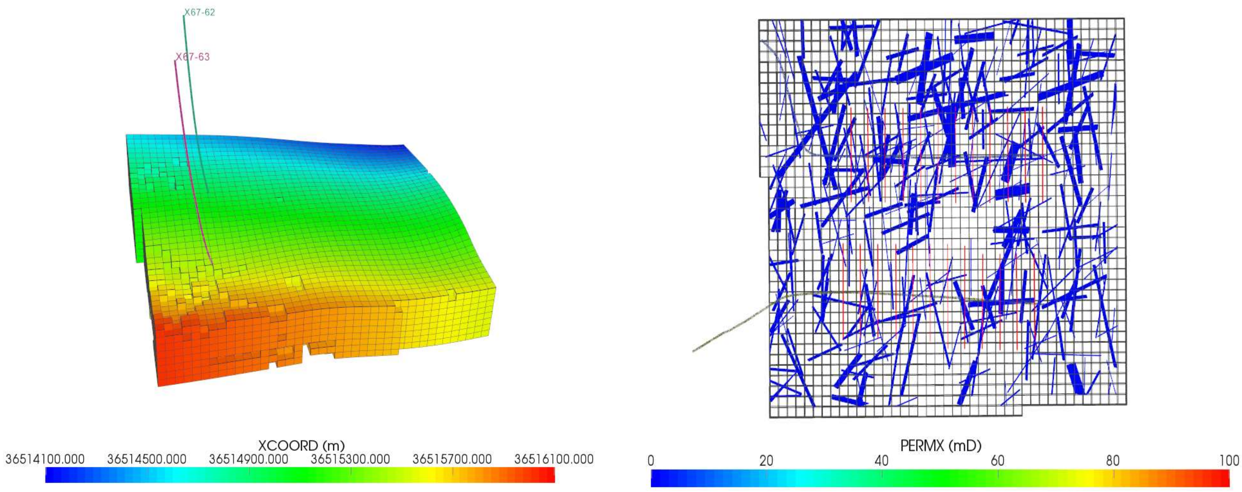


Figure 1. Simulation flowchart.

Reservoir Model. A heterogeneous numerical model was established based on the geological characteristics of the typical well group in the X oilfield, as shown in **Figure 2**. The grid was divided into 38×42×8, with a grid size of 40m×40m×10m. The typical well group includes two hydraulically fractured horizontal wells, X67-62 and X67-63, each with 12 fractures, totaling 24 hydraulic fractures. The fracture half-length is 160m, and the well spacing is 520m. Both hydraulic and natural fractures were modeled using the Embedded Discrete Fracture Model (EDFM).



(a)3D View of the numerical model (b)Fracture characterization

Figure 2. Schematic diagram of the numerical model for the typical well group in the X oilfield.

Basic Parameter. According to the data, the average permeability of the X oilfield is 0.0022 mD, and the average length of natural fractures is 150 m (less than the well spacing). The reservoir in the X oilfield has low matrix permeability and relatively short natural fracture lengths. The specific parameter are shown in **Table 1**.

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Table 1. Parameter Settings for the Numerical Model.

Parameter	Value	Unit
Matrix porosity	4.8	%
Matrix permeability	0.002	mD
Effective thickness	10	m
Natural fracture porosity	0.5	%
Natural fracture permeability	1	mD
Well spacing	300	m
Fractures half-length	100	m
Fracture spacing	150	m
Horizontal segment length	750	m
Initial oil saturation	60	%
Original Formation Pressure	14.7	MPa

Based on the crude oil formation fluid analysis report, a component model of the reservoir formation fluid was established. To facilitate numerical simulation calculations, the composition of the original formation fluid was categorized and combined into seven pseudo-components based on the results of relevant experimental well fluid composition tests. The initial content of each component is shown in **Table 2.** The CO_2 injection pressure calculated by the simulation software under miscibility conditions is 14.0 MPa, thus all simulations in this study are conducted under miscibility conditions.

Table 2. Pseudo-Component Model.

Component	Molecular Weight	Mole Fraction%
N_2	28.01	0.7
CO_2	44.01	0.7
C_1	16.04	22.5
C_2-C_3	38.18	17.8
C_4-C_6	68.42	13.4
C_7-C_{10}	112.66	13.8
C_{11+}	403.50	31.1

Relative Permeability Curves. The oil-water relative permeability curve and gas-liquid relative permeability curve for the X block are shown in the figures. The relative permeability curves reflect the flow patterns of oil, gas, and water in the reservoir. Due to the different flow patterns between the matrix and fractures, the flow in fractures is usually linear. Therefore, two sets of relative permeability curves are assigned to the matrix grid and the embedded and fractured fractures, as shown in **Figure 3**.

Well Control Condition Settings. In the CO_2 Huff-n-Puff model, the well control conditions are constrained by a maximum liquid production rate of 15 m^3/day. Taking into account field knowledge from the X block oilfield and calculations related to fracture pressure, the minimum bottom hole pressure for production wells is set at 5 MPa, while the maximum bottom hole pressure for injection wells is set at 35 MPa.

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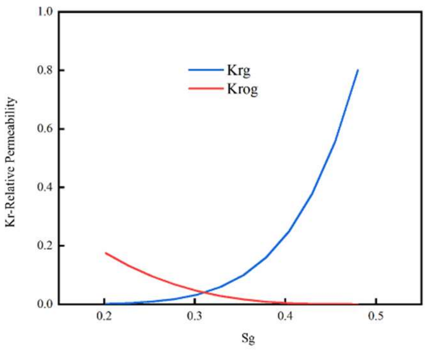
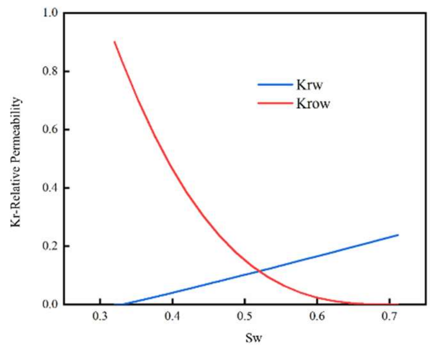
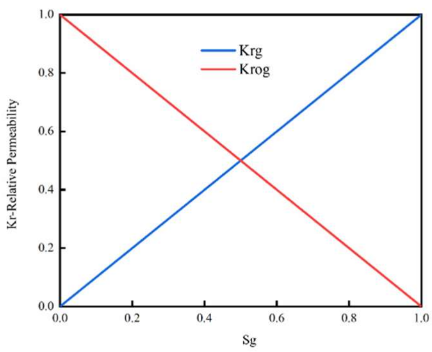


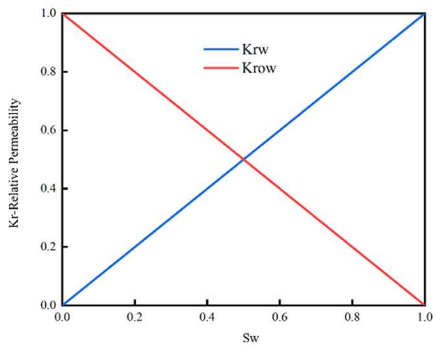
(a) Matrix Gas-Liquid Relative Permeability Curve



(b) Matrix Oil-Water Relative Permeability Curve



(c) Fracture Oil-Water Relative Permeability Curve



(d) Fracture Gas-Liquid Relative Permeability Curve

Figure 3. Relative Permeability Curves for the X Oilfield.

3. Results and Discussion

Comparison of CO_2 Continuous Injection and Huff-n-Puff Effects. To ensure comparability between the Huff-n-Puff and continuous injection methods, the total CO_2 injection volume for Huff-n-Puff is controlled to be the same as that for continuous injection. The specific Huff-n-Puff plan involves 3000 days of depleting production, followed by simultaneous CO_2 Huff-n-Puff operations for both wells for a total of 20 cycles. Each cycle lasts 300 days, including 120 days of injection, 30 days of shut-in, and 150 days of production, leading to a total Huff-n-Puff duration of 6000 days. The injection rate for each well is set at 5×10^4 m^3/day, and the injection pressure is set at 35 MPa.

The continuous CO_2 injection plan involves 3000 days of depleting production, after which one well switches to injection mode for continuous gas drive over 6000 days, with a daily injection rate of 1 × 10^5 m^3/day. The other well continues production for 6000 days.

To compare the oil production effects of continuous CO_2 injection and CO_2 Huff-n-Puff in the X block, the following parameters are set to values close to those in the X block: fracture permeability = 100 mD, half-length of fractured fractures = 100 m, well spacing = 300 m, and matrix permeability = 0.002 mD. The pressure field and CO_2 mole fraction distributions are compared at production durations of 6000 days and 9000 days, as shown in **Figure 4** and **Figure 5**.

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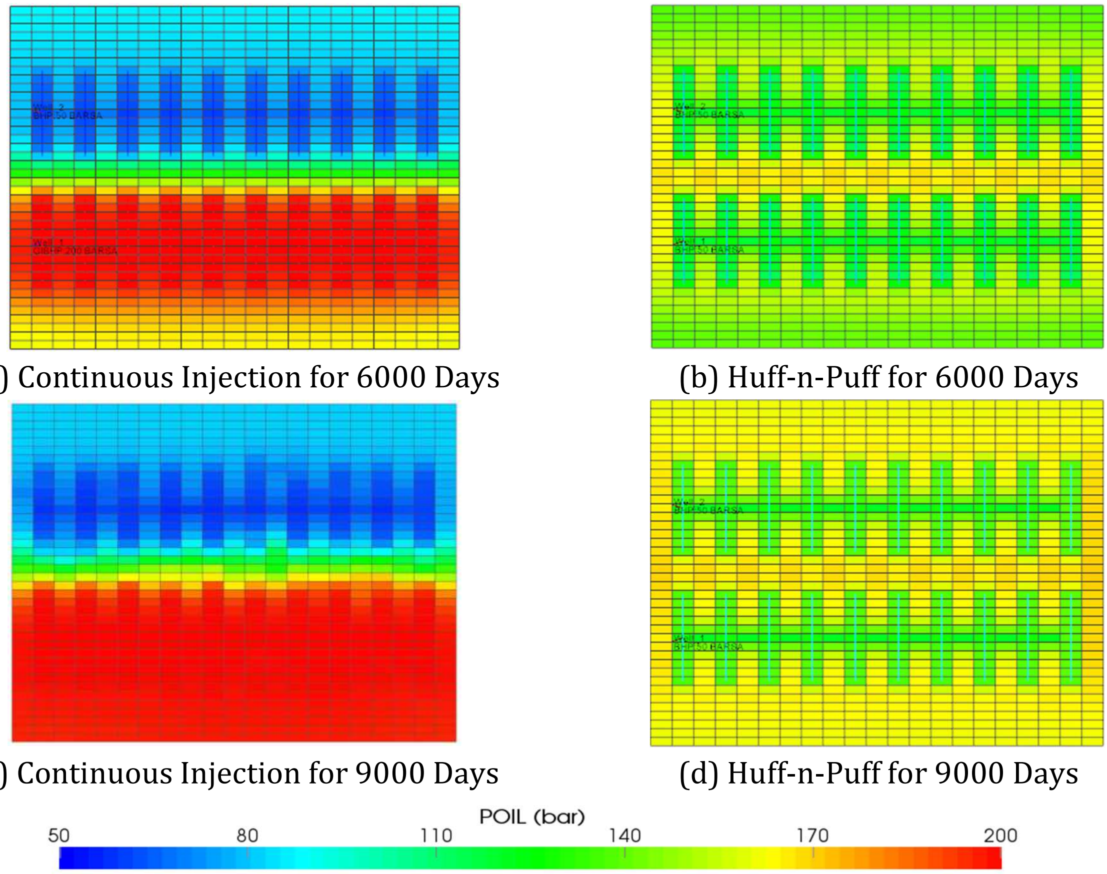


Figure 4. Comparison of Formation Pressure Fields for CO2 Continuous Injection and CO2 Huff-n-Puff.

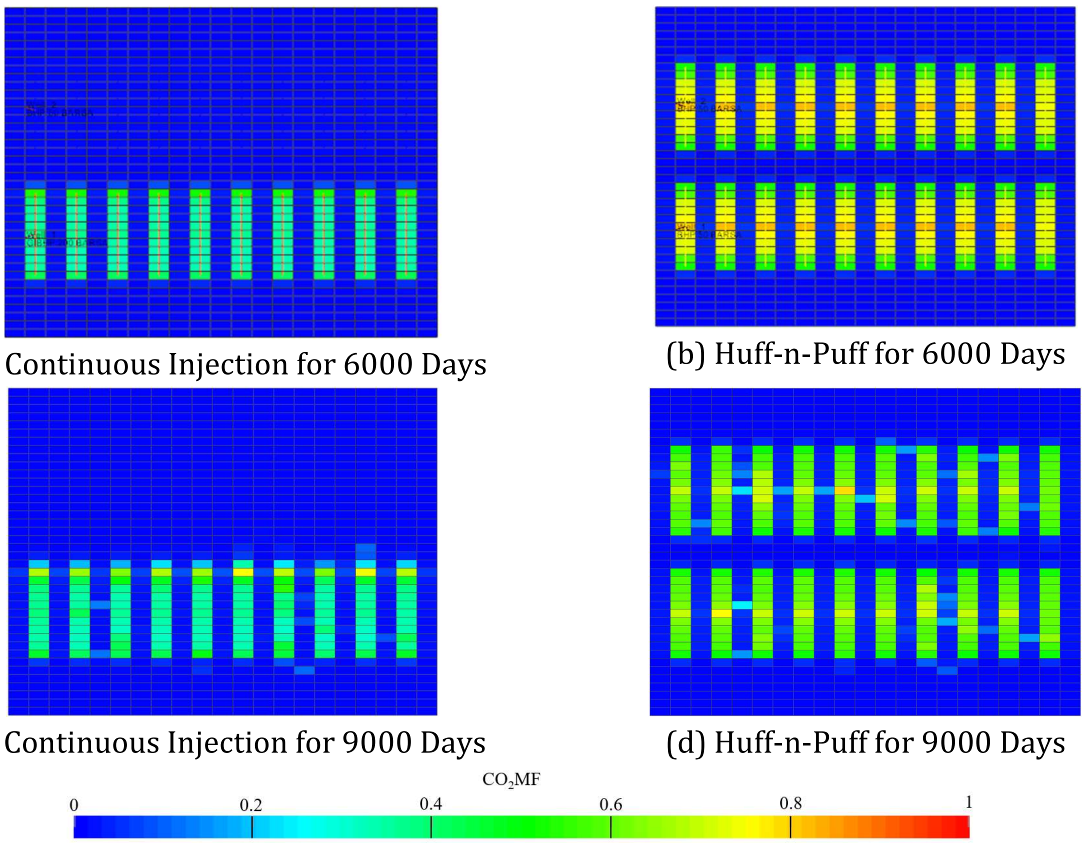


Figure 5. Comparison of CO2 Mole Fraction Distributions.

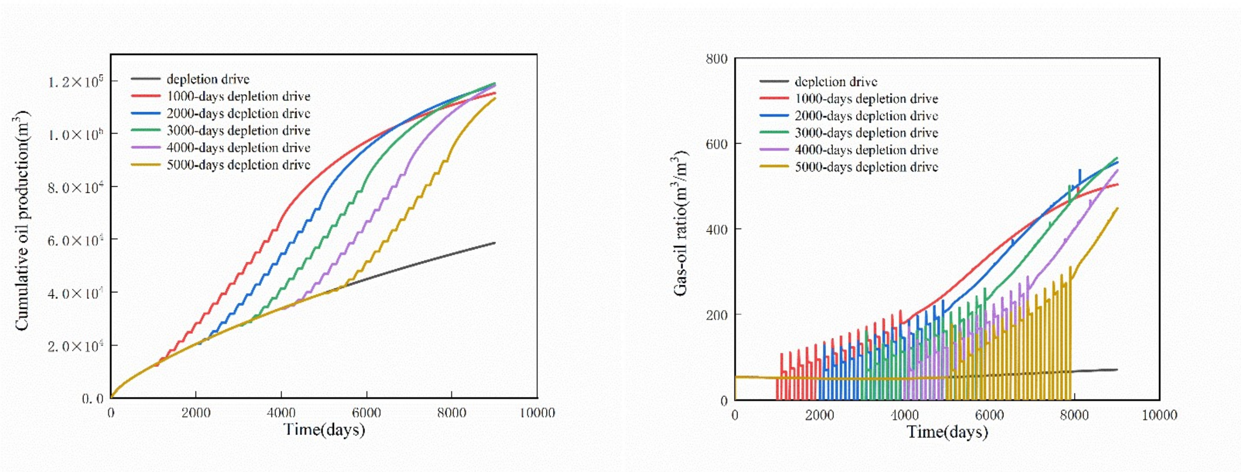
A comprehensive analysis of the pressure field and CO_2 mole fraction distribution indicates that, due to the short length of natural fractures in the X block, the oil recovery effect of continuous CO_2 injection is relatively poor. This is not only because of the low permeability of the matrix, which leads to insufficient injection capacity of the reservoir, but also because the short natural fractures prevent the injected CO_2 from forming an effective flow pathway between the two wells.

In contrast to continuous CO_2 injection, CO2 Huff-n-Puff can achieve good oil recovery in the X block's reservoir, which has low matrix permeability and short natural fractures. Analysis of the model's pressure field and CO_2 mole fraction distribution shows that CO_2 Huff-n-Puff employs injection and production through the same well, concentrating pressure drop and CO_2 diffusion around that well. This means that CO_2 does not need to flow from the injection well to the production well; instead, it can enhance oil recovery mechanisms in the vicinity of the single well, thereby increasing production.

Sensitivity Analysis of CO_2 Huff-n-Puff. Based on the comparisons in the previous section, the suitable CO_2 injection method for the X oil area has been determined to be CO_2 Huff-n-Puff. To clarify the impact of various Huff-n-Puff parameters on oil recovery, factors such as cumulative oil production, gas-to-oil ratio, and oil recovery rate are considered. Drawing from the results of the literature review in the first section, parameters for the CO_2 Huff-n-Puff project, namely the timing of Huff-n-Puff, periodic injection volume, daily injection rate, shut-in time, and number of cycles, will be subjected to a single-factor sensitivity analysis.

Timing of Huff-n-Puff. In the development of shale oil, it is common to first deplete the reservoir before implementing CO_2 Huff-n-Puff to enhance recovery. The goal is to make reasonable use of natural energy to extract oil during the early development phase. Before initiating gas injection, it is essential to utilize natural energy effectively while maintaining reasonable reservoir pressure, making the timing of CO_2 injection particularly crucial.

To study the impact of injection timing on Huff-n-Puff effectiveness, depleting development was carried out first, followed by gas injection after 1000, 2000, 3000, 4000, and 5000 days of depletion. Each Huff-n-Puff cycle lasted 200 days, including 60 days of injection, 30 days of shut-in, and 110 days of oil production, with a total of 15 cycles conducted. Each scenario had a Huff-n-Puff duration of 4000 days, with a uniform injection rate set at 4×10^4 m^3/day. After Huff-n-Puff, the simulation predicted a depletion phase lasting 9000 days. Cumulative oil production simulation results are shown in **Figure 6**, and pressure fields for different injection start timings are shown in **Figure 7**.



(a) Cumulative oil production (b) Gas-oil ratio

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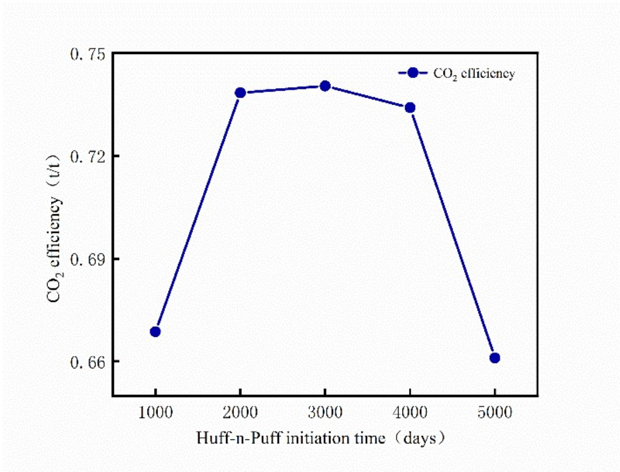
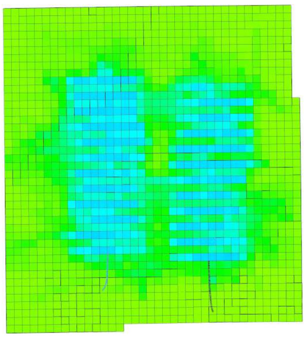
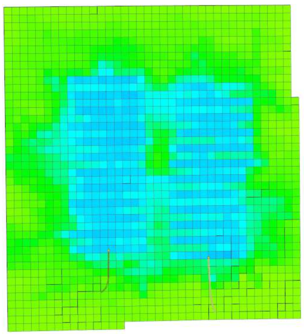


(c) CO2 efficiency

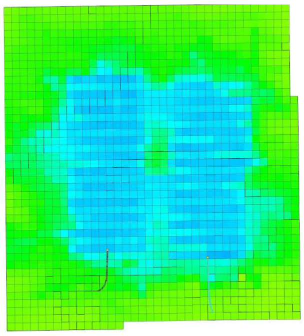
Figure 6. Simulation Results for Different Huff-n-Puff Start Times.



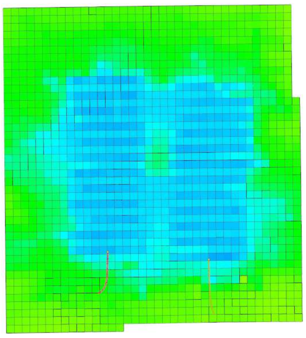
(a) Huff-n-Puff Start Time at 500 Days



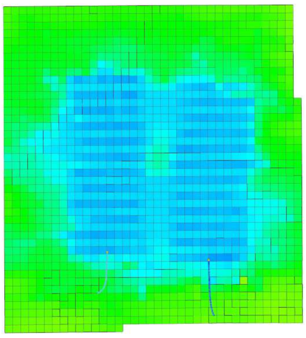
(b) Huff-n-Puff Start Time at 1000 Days



(c) Huff-n-Puff Start Time at 1500 Days



(d) Huff-n-Puff Start Time at 2000 Days



(e) Huff-n-Puff Start Time at 2500 Days

Figure 7. Formation Pressure Fields at Different Huff-n-Puff Start Times.

From the cumulative oil production curves, it can be observed that under the condition where the total duration of huff-n-puff remains consistent across all schemes, the earlier the huff-n-puff starts, the lower the cumulative oil production at the end of the prediction. Conversely, the later the huff-n-puff begins, the greater the cumulative oil production at the end of the simulation. However, as the start time of huff-n-puff is delayed, the rate of increase in cumulative oil production gradually slows down. This is because if the huff-n-puff starts too early, the reservoir pressure is still relatively high, as shown in **Figure 7(a)**, where the pressure drawdown range is small at a 500-day start time. Injecting CO_2 at this stage may result in

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underutilization of the natural reservoir energy. On the other hand, if the gas injection starts too late, as shown in **Figure 7(e)**, it could lead to insufficient energy replenishment in the reservoir, which causes the cumulative oil production curve to increase at a slower rate.

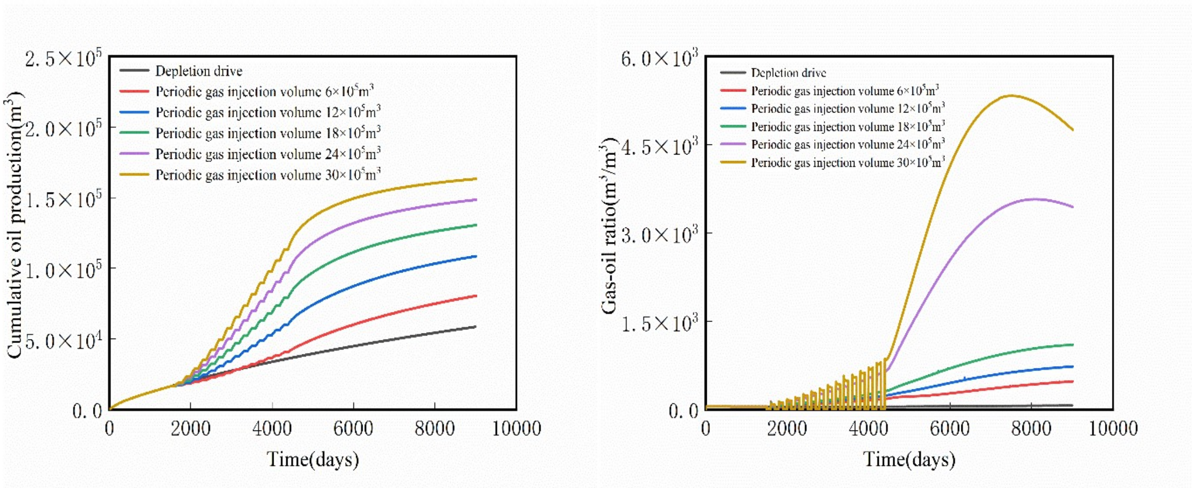
Cyclic CO_2 Injection Volume. Cyclic CO_2 injection volume refers to the total amount of CO_2 injected per well in each huff-n-puff cycle. Generally, a larger injection volume can better supplement reservoir energy and allow more CO_2 to enter the reservoir, enhancing oil recovery mechanisms and increasing cumulative oil production. However, excessive CO_2 injection can lead to a high gas-oil ratio, causing gas breakthrough, as well as wastage of CO_2 resources, negatively affecting economic efficiency.

To investigate the impact of different cyclic injection volumes on cumulative oil production and CO_2 replacement efficiency, this section sets the injection period as follows: both wells inject CO_2 simultaneously for 60 days, soak for 30 days, and produce for 110 days. Five different cyclic injection volumes are set, with the specific parameters listed in **Table 3**.

Table 3. Cyclic Injection Volume Design

Daily Injection Volume ($\times 10^4 m^3$)	Cycle Injection Duration(days)	Cycle Injection Volume ($\times 10^5 m^3$)
1	60	6
2	60	12
3	60	18
4	60	24
5	60	30

The simulation results for the five different injection schemes are shown in **Figure 9**. Analyzing the trends, it can be seen that as the total cycle injection volume increases, the corresponding cumulative oil production also gradually increases. However, by examining the curve trends, it is evident that the increase in cumulative oil production begins to slow down slightly when the cycle injection volume reaches 24×10^5 m^3. The gas-oil ratio curve indicates that when the cycle injection volume reaches 24×10^5 m^3, the corresponding gas-oil ratio rises too quickly, which is caused by the excessive CO_2 injection. Therefore, the increase in cumulative oil production slows down, indicating that the cycle injection volume for the huff-n-puff process should not be too large.



(a) Cumulative oil production (b) Gas-oil ratio

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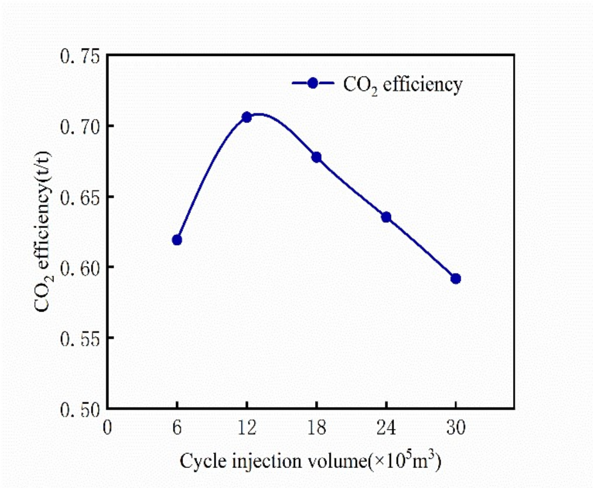

(c) CO2 efficiency

Figure 8. Simulation results for different total cycle injection volumes.

The trend of the oil replacement ratio indicates that it increases sharply in the early stages with the rise in cycle injection volume, peaking at 12×10^5 m^3. After that, as the cycle injection volume increases, the oil replacement ratio begins to decline. From the gas-oil ratio curve, it can be observed that the gas-oil ratio increases with the cycle injection volume, and when the cycle injection volume reaches 30×10^5 m^3, the gas-oil ratio rises too quickly due to excessive CO_2 injection. Therefore, considering the three factors of cumulative oil production, oil replacement ratio, and gas-oil ratio, the cycle injection volume for the CO_2 huff-n-puff method should not be too large while maintaining high levels of cumulative oil production and oil replacement ratio.

Injection Rate. During the CO_2 huff-n-puff process, the injection rate has different effects on reservoir energy supplementation. If the injection rate is too fast, it may cause CO_2 breakthrough, reducing the final cumulative oil production. On the other hand, if the injection rate is too slow, reservoir energy supplementation will be insufficient, and the oil recovery effect of CO_2 will not be fully utilized, also leading to lower final cumulative oil production. Therefore, when implementing CO_2 huff-n-puff, it is essential to balance the injection rate and CO_2 utilization efficiency. To discuss the impact of injection rate on cumulative oil production, while keeping the cycle gas injection volume constant, five different injection rates were set: 1×10^{4}m^3, 1.5×10^{4}m^3, 3×10^{4}m^3, 6×10^{4}m^3, and 9×10^{4}m^3. In each scenario, the shut-in time was set at 30 days, and the production time at 110 days. The specific parameters for each scenario are shown in **Table 4**.

Table 4. Injection Rate Parameter Design.

Injection Rate (×10^{4}m^3/d)	Gas Injection Duration (days)	Cyclic Gas Injection Volume (m^3)	Cyclic Huff-n-Puff Duration (days)
1	180	18	4800
1.5	120	18	4200
3	60	18	3000
6	30	18	2550
9	20	18	2400

The simulation results corresponding to the five injection speeds are shown in **Figure 9**. The analysis indicates that as the injection speed increases, the cumulative oil production also gradually increases. The cumulative oil production shows an increasing trend until the injection speed reaches 6×10^4 m^3. Beyond this point, further increases in injection speed result in little

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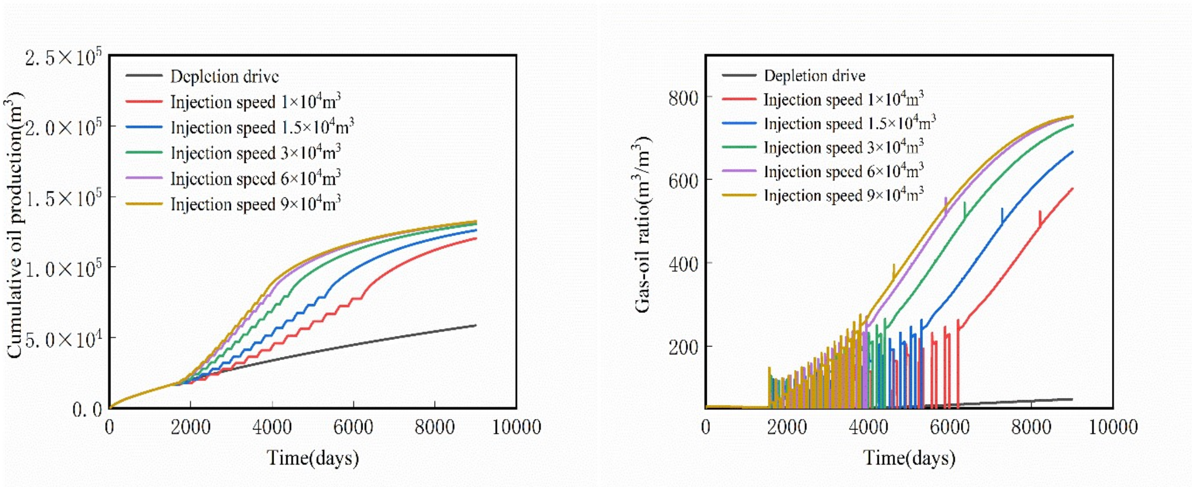
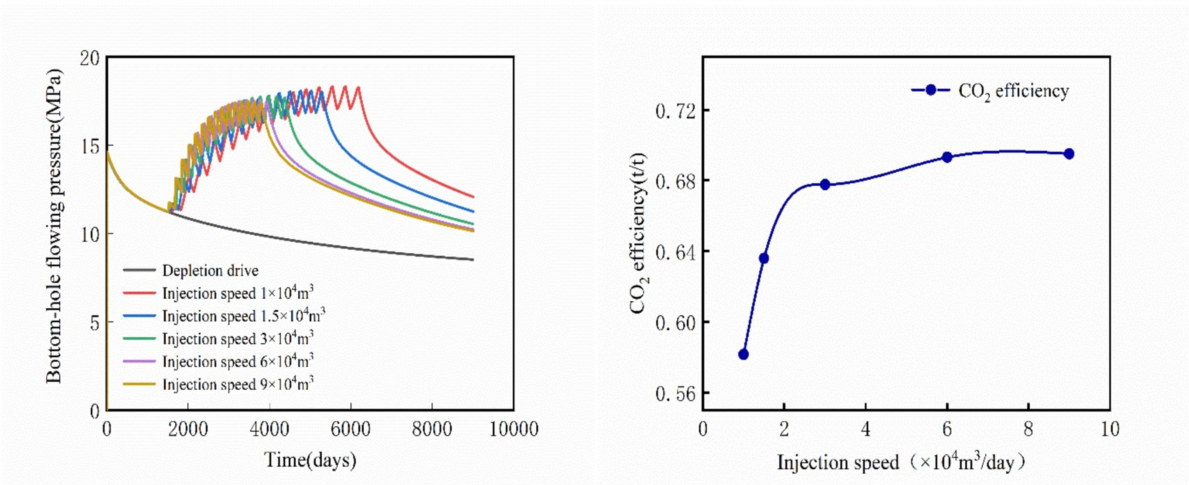
to no change in cumulative oil production. This is due to the fast injection speed causing insufficient contact between the CO_2 gas and the formation oil, which may also push the oil towards the distant well areas. The curve for the oil replacement rate shows that the replacement rate also increases with the injection speed. Once the injection speed reaches $6×10^4$ m^3, the replacement rate stabilizes, and any further increase in injection speed results in only a marginal increase in the replacement rate, leading to reduced CO_2 utilization efficiency and economic benefits.



(a) Cumulative oil production (b) Gas-oil ratio



(c) Bottom-hole pressure (c) CO2 efficiency

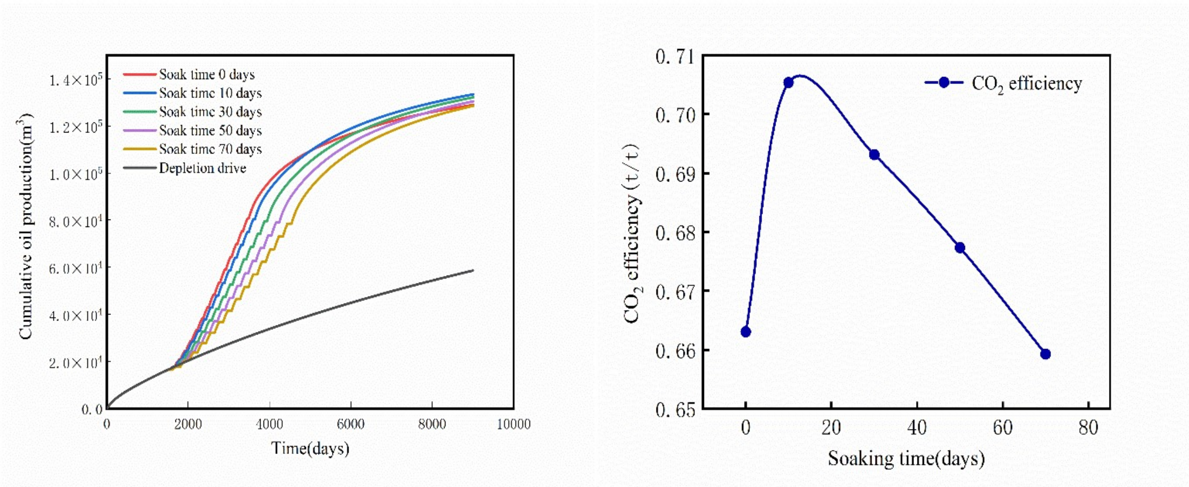
Figure 9. Simulation Results of Different Injection Speeds.

From the gas-oil ratio curve, it can be seen that the gas-oil ratios for the five schemes remain at a low level, without causing gas breakthrough. The bottom hole pressure curve indicates that a higher injection speed results in a greater increase in bottom hole pressure during the early production phase. Additionally, as the injection speed increases, the time to reach the set total CO_2 injection amount is shorter, leading to a longer production time after the injection phase, which allows for more efficient utilization of the supplemental energy.

Soak Timing. In the CO_2 huff-n-puff process, the soaking time is a critical aspect that affects the duration of CO_2 reacting with crude oil during each injection cycle. If the soaking time is insufficient, it may lead to incomplete reactions between CO_2 and crude oil, reducing CO_2 utilization and weakening the production enhancement effect. Conversely, if the soaking time is too long, it may result in insufficient production time, which similarly affects the production enhancement effect. Since CO_2 requires a certain amount of time to diffuse and fully interact with crude oil, the wellhead is typically closed for a period after CO_2 is injected into the formation.

Due to the different geological characteristics and fluid properties of various reservoir types-such as formation temperature, permeability, formation pressure, and crude oil viscosity-along with variations in production parameters, these factors can influence the reasonable setting of soaking time.

To investigate the impact of soaking time on cumulative oil production, five different soaking times were set: 0 days, 10 days, 30 days, 50 days, and 70 days, allowing for a more comprehensive discussion of the best practices for CO_2 huff-n-puff to improve the cumulative oil production effect of the model. The simulation results for different soaking times are shown in **Figure 10**.

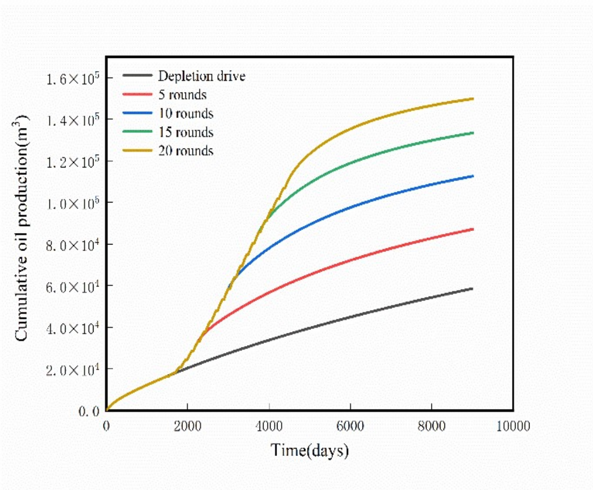


(a) Cumulative oil production (b) CO2 efficiency

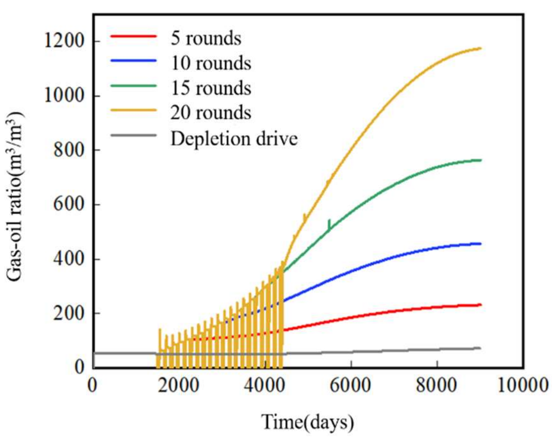
Figure 10. Simulation Results of Cumulative Oil Production under Different Soaking Times.

The analysis of cumulative oil production shows that with the implementation of soaking, the cumulative oil production decreases as the soaking time increases. The highest cumulative oil production occurs when the soaking time is 10 days, while the cumulative oil production is lower at 0 days, i.e., without soaking. Without soaking, CO_2 does not fully exert its swelling and viscosity-reducing effects, leading to less effective oil production enhancement. At 70 days of soaking, the cumulative oil production is also low because, although CO_2's effects are more pronounced with longer soaking, the oil production lost during the non-production period outweighs the increase in oil production. The oil displacement efficiency curve shows a trend of first increasing and then decreasing, reaching its maximum at 10 days of soaking.

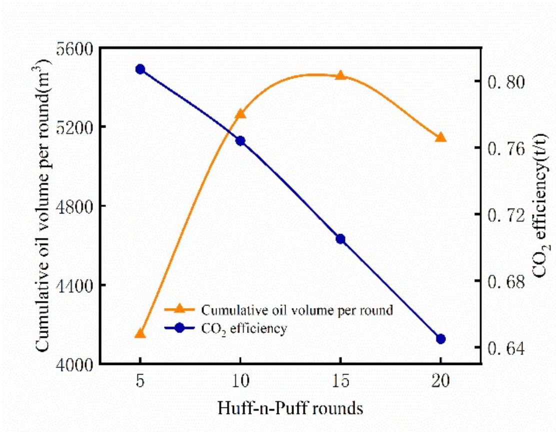
Huff-n-Puff Rounds The number of Huff-n-Puff cycles affects both injection and production times. To analyze the impact of the number of cycles on cumulative oil production, four different Huff-n-Puff schemes were set up. For each scheme, the injection rate was set to 6×10^4 m^3, with an injection duration of 30 days, shut-in time of 10 days, and production time of 110 days. The number of Huff-n-Puff cycles was varied to 5, 10, 15, and 20 cycles. The simulation results for these four schemes are shown in **Figure 11**.



(a) Cumulative oil production



(b) Gas-oil ratio



(c) CO2 Efficiency and Incremental Oil Production per Cycle

Figure 11. Simulation Results for Different Injection Cycles.

Analysis of the cumulative oil production curve shows that as the number of injection cycles increases, the cumulative oil production also increases, but the increment in oil production decreases. The gas-oil ratio curve indicates that with the increase in injection cycles, the gas-oil ratio gradually rises, leading to decreased economic efficiency. Therefore, the number of injection cycles should not be too high.

Optimization of CO_2 Huff-n-Puff Scheme. Based on the results of the single-factor sensitivity analysis in the previous section, a multi-factor comprehensive parameter optimization is conducted for the X block to evaluate the main controlling factors affecting the CO_2 Huff-n-Puff production enhancement effect. In the multi-factor experiments, orthogonal design obtains comprehensive information with fewer trials, considering the independence of factors to improve experimental efficiency and comprehensiveness.

Table 5. Orthogonal Test Design Table.

Level Number	Huff-n-Puff Start Timing (days)	Total Injection Volume per Cycle ($\times10^5 m^3$)	Injection Rate ($\times10^4 m^3$)	Soaking Time (days)	Huff-n-Puff rounds (rounds)
1	500	12	1	10	5
2	1000	24	1.5	30	10
3	1500	36	3	50	15
4	2000	48	6	70	20

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Considering the complex effects of factors such as the start time of Huff-n-Puff, periodic gas injection volume, soaking time, and the number of cycles on production, a 5-factor orthogonal test is designed for each factor, with each factor comprising 4 levels, as shown in **Table 5**.

Based on the current factors and levels, L16 (4^5) was selected as the design table for this orthogonal experiment, resulting in a total of 16 simulation schemes. The specific injection schemes and results are shown in **Table 6**.

Table 6. Comparison of Orthogonal Experiment Results.

Scheme Number	Huff-n-Puff Start Timing (days)	Total Injection Volume per Cycle ($\times 10^5 m^3$)	Injection Rate ($\times 10^4 m^3$)	Soaking Time (days)	Huff-n-Puff rounds (rounds)	Cumulative Oil Production (m^3)
1	500	12	1	10	5	50069
2	500	24	1.5	30	10	76189
3	500	36	3	50	15	102504
4	500	48	6	70	20	132268
5	1000	12	1.5	50	20	80262
6	1000	24	1	70	15	91813
7	1000	36	6	10	10	102224
8	1000	48	3	30	5	86290
9	1500	12	3	70	10	65601
10	1500	24	6	50	5	68613
11	1500	36	1	30	20	117491
12	1500	48	1.5	10	15	128192
13	2000	12	6	30	15	74542
14	2000	24	3	10	20	110372
15	2000	36	1.5	70	5	73991
16	2000	48	1	50	10	100104

For the evaluation method of the orthogonal experiment, this paper uses the commonly used range analysis method to measure the primary and secondary relationships of the influencing factors for each indicator. The results are presented as follows, as shown in **Table 7**.

Table 7. Range Analysis Table for Cumulative Oil Production.

Number	Huff-n-Puff Start Timing (days)	Total Injection Volume per Cycle ($\times 10^5 m^3$)	Injection Rate ($\times 10^4 m^3$)	Soaking Time (days)	Huff-n-Puff rounds (rounds)
$\overline{K}_1$	90007	67368	87869	97964	68240
$\overline{K}_2$	87397	83747	88158	88878	85779
$\overline{K}_3$	95474	98302	91192	87370	97013
$\overline{K}_4$	88502	111963	94161	87168	110348
R	8077	44595	6292	10796	42108

In this context, $\overline{K}_i$ represents the average cumulative oil production corresponding to each parameter's value, while R indicates the range, which reflects the extent of the parameter's influence on the result; a larger value signifies a greater impact on the outcome, and vice versa.

To more intuitively illustrate the effect of varying each parameter on cumulative oil production, the average cumulative oil production values corresponding to different parameter values are depicted in **Figure 12**.

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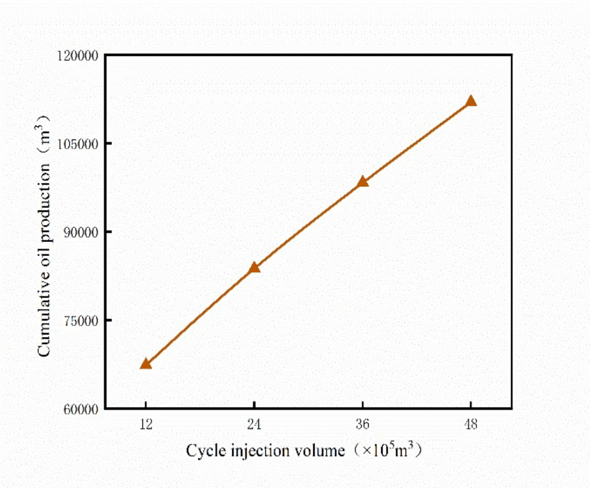
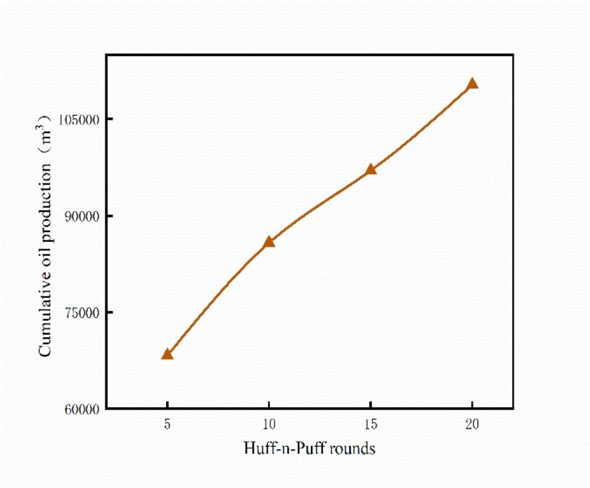
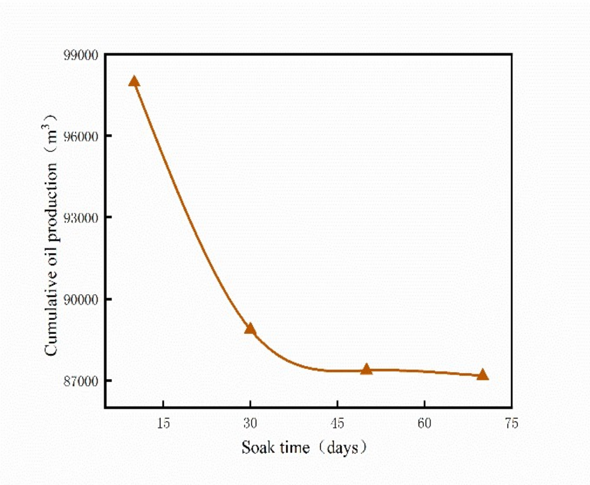


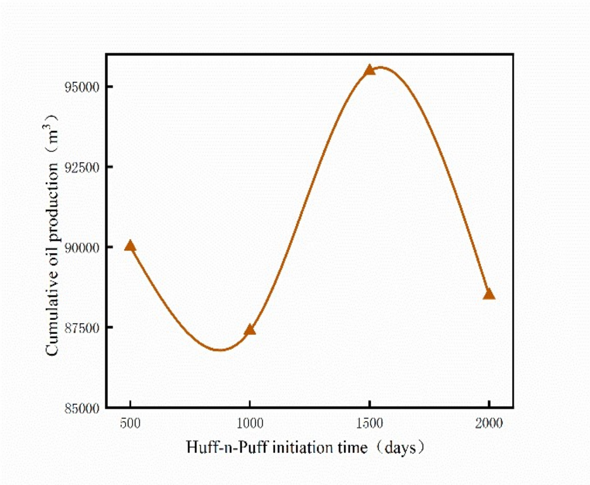
(a) Cumulative Oil Average Value - Single Well Cycle Injection Volume



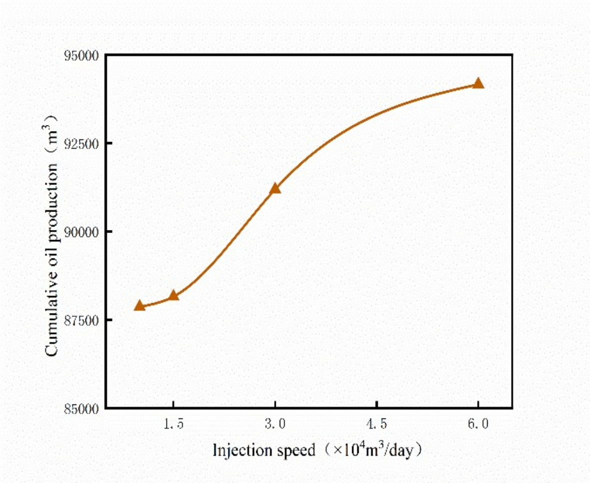
(b) Cumulative Oil Average Value - Huff-n-Puff Rounds



(c) Cumulative Oil Average Value - Soaking Time



(d) Cumulative Oil Average Value - Huff-n-Puff Start Timing



(e) Cumulative Oil Average Value - Injection Rate

Figure 12. Cumulative Oil K-value Variation.

Through the analysis of the data in the table, the ranking of the weights influencing cumulative oil production from highest to lowest is as follows: single well periodic injection volume > number of huff-and-puff cycles > soaking time > start time of huff-and-puff > injection rate. The

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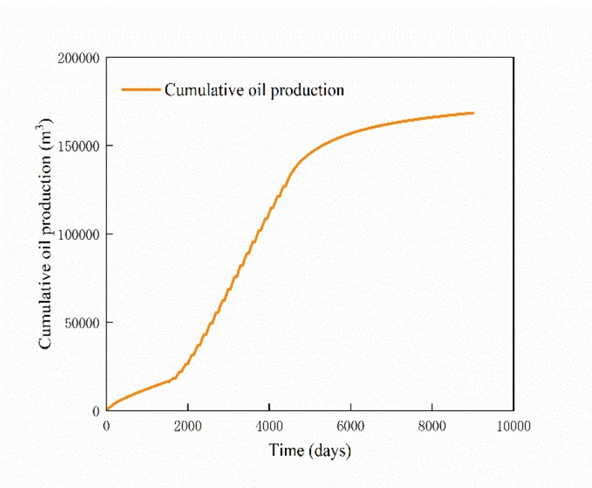
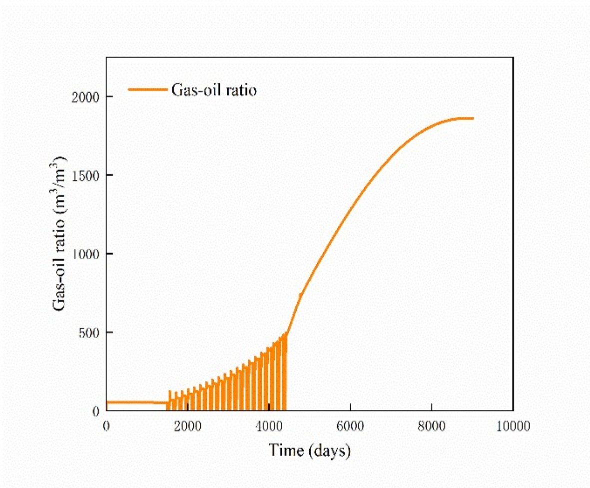
effects of periodic injection volume and the number of huff-and-puff cycles on cumulative oil production are significantly greater than those of the other three parameters; therefore, these two should be prioritized when selecting optimal parameter values.

From the analysis of the curves, it is evident that each parameter value corresponds to a maximum cumulative oil production. Taking this into consideration, the final selected parameter values for the model are: (a) single well periodic injection total volume: 4.8×10^6 m^3; (b) number of huff-and-puff cycles: 20; (c) soaking time: 10 days; (d) start time of huff-and-puff: 1500 days after depletion extraction; (e) injection rate: 6×10^4 m^3/day.

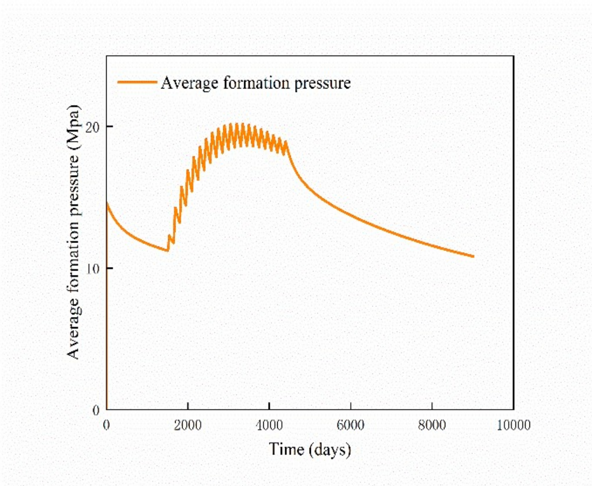
Based on the results of the parameter optimization, the cumulative oil production during the production period of the optimized plan for the X oil zone is 1.6×10^5 m^3, which is an increase of 2.87 times compared to depletion extraction. The simulation results corresponding to the optimized plan during the production period are shown in **Figure 13**.



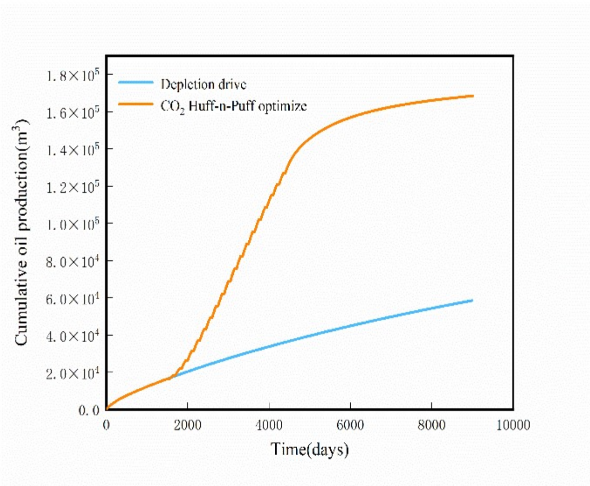
(a) Cumulative oil production



(b) Gas-oil ratio



(c) Average formation pressure



(d) Cumulative Oil Production Comparison Before and After Optimization

Figure 13. Simulation Results Under the Optimized Scheme.

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4. Conclusion

This study conducts a sensitivity analysis of CO_2 huff-n-puff in the X oil block shale reservoir. Based on the actual block, an optimization scheme for CO_2 huff-n-puff to enhance oil recovery was developed. The results obtained from this research and analysis are as follows:

Based on numerical simulation methods and geological characteristic data of the X oil block, a numerical model was established to compare the formation stress field and CO_2 molar fraction distribution under two injection methods: CO_2 continuous injection and CO_2 huff-n-puff. The discussion on the applicability of both methods indicates that CO_2 huff-n-puff is more suitable for reservoirs in the X oil block with shorter natural fracture lengths and lower matrix permeability.

CO_2 huff-n-puff was determined to be the appropriate enhanced oil recovery method based on the geological characteristics of the X oil block. By evaluating cumulative oil production and gas-to-oil ratio, the influence of parameter changes on enhancement effects was analyzed. Simulation results show that there are optimal values for huff-n-puff timing, periodic injection volume, injection speed, shut-in time, and number of huff-n-puff cycles, leading to higher cumulative oil production and gas-to-oil ratio.

Based on the results of the single-factor analysis, an orthogonal experiment was conducted, ultimately optimizing the CO_2 huff-n-puff scheme to: (1) single-well periodic total injection volume: 4.8×10^6 m^3; (2) number of huff-n-puff cycles: 20; (3) shut-in time: 10 days; (4) huff-n-puff start time: 1500 days after depletion production; (5) injection speed: 6×10^4 m^3/day. Under the optimized scheme, the cumulative oil production reached 1.6×10^5 m^3, compared to 5.8×10^4 m^3 for depletion production, resulting in a 2.87-fold increase in cumulative oil production.

Conflicting Interests

The author(s) declare that they have no Conflicting interests.

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