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Synergetic CO_2 Huff-n-Puff for Edge-Water Fault-Block Reservoir: Laboratory Experiment and Numerical Simulation

Hongda Hao, Jirui Hou, Fenglan Zhao, Zhixing Wang, Zhongfeng Fu, Wengfeng Li, Peng Wang, Meng Zhang, Guoyong Lu and Jian Zhou, China University of Petroleum (Beijing)

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Abstract

As an effective method for resource utilization, CO_2 huff-n-puff can be utilized to reduce CO_2 emissions and enhance oil recovery in edge-water flock-block reservoir, which was implemented in Jidong Oil Field, China since 2008 with oil production of 6.5×10^4 bbls by 2015. During operation period, synergetic effect was observed in adjacent wells with water cut drops and oil increments in a horizontal well group. Experimental and numerical simulations were conducted to investigate synergetic mechanisms of CO_2 huff-n-puff. 3D physical models with a horizontal well group and edge-water-driving system were established in laboratory to simulate the edge-water fault-block reservoir. The formation mechanisms and influence factors of synergetic CO_2 huff-n-puff were studied through laboratory experiments. Base reservoir model was also built to further discuss the synergetic types and injection allocations for CO_2 huff-n-puff in horizontal well group.

Synergetic CO_2 huff-n-puff is a smart gas cycling strategy for the horiontal well group to balance the formation pressure and replace the interwell oil. Experimental and numerical results showed that after CO_2 injected into low tectonic position of the reservoir, synergetic effect could be observed in high position well with water cut drops and oil increments. The mechanisms of synergetic effect can be recognized as formation energy supplement, gas sweeping, gravity segregation and CO_2-assisted edge-water driving. The stratigraphic dip and heterogeneity are advantages for the formation of synergetic effect. The synergetic types of CO_2 huff-n-puff can be summarized as single-well synergy and multi-well synergy. For single-well synergy, edge-water invasion can be effectively controlled by energy supplement after CO_2 injected into relatively low position well. For multi-well synergy, better synergetic effect and remaing oil replacement can be achieved after gas injected through different positions of the well group. The development efficiency of synergetic CO_2 huff-n-puff can be enlarged with 700t CO_2 injected into low position well + 100t CO_2 into high position well, and about 5767.9 bbls oil of the well group could be recovered with the soaking time of 50d.

Key words: CO_2 huff-n-puff; fault-block reservoir; horizontal well; edge water; synergetic effect

1 Introduction

As the highly water cut and less potential of enhancing oil recovery in conventional oil reservoirs, the complex oil reservoirs including fault-block reservoirs become the new exploratory development targets which are widely distributed both in China and abroad (Denham R., 1965; Ma C., et al, 1982; Nitzberg K. and Broman W., 1992; Wu Y., et al, 2012). Complex fault-block reservoirs are usually with the properties of broken structures, multiple reservoir types, complicated oil-water systems, etc., and are usually with lower producing levels compared with conventional oil reservoirs (Yu S., et al, 1995; Dai S., et al, 2008). In order to improve the productivity and enhance oil recovery of fault-block reservoirs, various EOR technologies have been operated in the oil field including gas injection, miscible and immiscible CO_2 flooding, steamflooding, and chemical combination flooding (Laidlaw W., et al, 1986; Spivak A., et al, 1990; Lim F., et al, 1993; Lu L. and Liu B., 1998; Zhu Y., et al, 2015).

Horizontal wells are usually applied in fault block reservoirs to enlarge the drainage area and improve the productivity. Horizontal wells can overcome the compartments, sealing faults and other lateral discontinuities, and obtain economic and sustained productions of complex reservoirs (Zhou H., et al, 2006; Naderi M., et al, 2015). However, if the reservoirs were adjacent to edge or bottom aquifers, the water invasion problem may occur seriously during the development period of oil field. Water coning and oil bypassing caused early water production and low productivity of crude oil with plenty of oil unrecovered in the edge-water or bottom water driving reservoirs (Hernandez J. and Wojtanowicz A., 2006; Han Z., et al, 2009). Different methods were proposed to restrain the water invasion including production rate control, production pattern management, barrier fluids injection and formation damage inducement (Karp J., et al, 1962; Seright R., et al, 2001; Zeinijahromi A., et al, 2015). Treating strategy should be designed according to actual geology and development of specific oil field to obtain preferable oil recovery in fault block reservoirs with edge-water or bottom-water acquifer.

CO_2 huff-n-puff is an effective method to enhance oil recovery in tertiary process. The mechanisms of CO_2 huff-n-puff to enhance oil recovery are oil viscosity reduction, oil swelling, well-bore damage removal, solution gas driving, vaporization of light components, water relative permeability reduction and interfacial tensions reduction (Mohammed-Singh L., et al, 2006). Towler B. and Wagle Y. (1992) pointed out that the relative-permeability hysteresis and reservoir pressure increase are the significant mechanisms for the success of CO_2 huff-n-puff process. The miscibility between oil and gas also has significant influence on enhancing oil recovery, and Torabi F., et al (2012) revealed that the oil recovery of near-miscible CO_2 huff-n-puff was greatly improved compared with immiscible CO_2 huff-n-puff. CO_2 huff-n-puff technology was firstly utilized to enhance the oil recovery of heavy oil reservoirs (Sayegh S. G., et al, 1984). Then, Monger T. and Coma J. (1988) proposed that CO_2 huff-n-puff process can be utilized to enhance oil recovery of light oil with larger slug volume, longer soak period, thicker interval and lower prior water cut. Recent years, the application of CO_2 huff-n-puff has been extensive from conventional oil reservoirs to unconventional oil reservoirs, from simple oil reservoirs to complex oil reservoirs (Sorensen J., et al, 2011; Vinassa M., et al, 2015; Ma J., et al, 2015; Sun J., et al, 2016). Moreover, novel applications of CO_2 huff-n-puff has been proposed to enhance the oil recovery. For example, Simpson M. (1988) proposed that the CO_2 huff-n-puff can be utilized to restrain the bottom water invasion of the oil reservoir, and the oil production of each well can increase to $32m^3/d$ after gas injection. The decreasing in fractional flow of water was caused by the oil swelling and viscosity reduction, which shows an enlightenment of water control with CO_2 huff-n-puff in the edge-water flock-block reservoir. Li Z., et al (2011) proposed CO_2 and viscosity breaker assisted steam huff and puff technology for horizontal wells was effective in reducing viscosity and improving production of super-heavy oil reservoirs with deep and thin layers, deep and heavy layers, shallow and thin layers. In-situ CO_2 huff-n-puff was designed by Wang Y., et al (2015) to enhance oil recovery of fault block reservoirs. Large amount of CO_2 was generated near the wellbore formation by adding reagents into the formation, which can decrease the reservoir temperature near the wellbore by 5°C and increase the oil production by 56%.

2 Background

One fault block reservoir with sufficient edge-water acquifer is located in Jidong Oil Field, China. The oil-bearing area of the block is 2.26 ft^2 with geological reserves of 328.6×10^4 bbls and recoverable reserves of 65.75×10^4 bbls. Stratigraphic dip of the block is 15-22°, the reservoir depth is 1732.1 m, the water/oil contact is 1735 m, and the reservoir thickness is 26.8 m. The formation temperature is 333.15 K (60℃) and initial formation pressure is 17.03 MPa. The average porosity of the reservoir is 25.9%, and the average permeability is 667×10^{-3} μm^2. The density of crude oil is 0.87 g/cm^3 and the viscosity is 39.5 mPa·s under the formation temperature of 333.15 K.

A horizontal well group including 8 wells was located in the block, and the block was initially developed by edge-water driving. Although the oil production rate was high in the early stage of the development, it declined quickly with serious edge-water invasion. The water cut of several wells which were adjacent to the aquifer reached 99%. Because of the serious edge-water invasion, the oil recovery was less than 10% at the end of natural depletion period.

CO_2 huff-n-puff process was then conducted after natural depletion period with an initial intention to restrain the water invasion and improve the productivity of individual well. CO_2 was firstly injected into horizontal well of P-3, which was located in low tectonic position of the block and was adjacent to the edge-water aquifer. After 425 t of CO_2 injected into the formation, the water cut of P-3 decreased from 99% to 77.9%, and the oil was recovered by 428.2 bbls. More interestingly, a responding well of P-2 was observed with the response of water cut decreasing from 99% to 80.5% and oil increment by 267.1 bbls (As shown in Table 1). Since the responding well of P-2 was adjacent to P-3 and located in relatively high position of the block, synergetic effect of CO_2 huff-n-puff can be speculated based on the pilot test.

Table 1 Result of CO_2 huff-n-puff in pilot test

Well		Tectonic position	Water cut/%		Incremental oil production/bbls
			Before CO_2 huff-n-puff	After CO_2 huff-n-puff	
Injection well	P-3	Low	99	77.9	428.2
Responding well	P-2	high	99	20.5	267.1

In order to prove the existence of synergetic effect caused by CO_2 injection and study the mechanisms and influence factors of synergetic CO_2 huff-n-puff in horizontal well group, a large experimental device including 3D physical models, horizontal well simulation system, and edge-water-driving system was established in the laboratory to simulate the edge-water fault-block reservoir. A base reservoir model was also built to further discuss the synergetic types and injection allocations for CO_2 huff-n-puff in horizontal well group.

3 Experiments

3.1 Materials

The oil sample and water were collected from the block of Jidong Oil Field, China. The density of formation oil is 0.87 g/cm^3, the viscosity is 39.5 mPa·s and the gas/oil ratio is 42.42$m^3/^3$ under the formation temperature of 333.15 K (60C°). The composition of formation oil is detailed in Table 2. The minimum miscible pressure (MMP) measured by slim tube test is 24.39MPa, and the initial formation pressure is 17.03MPa. The salinity of the formation water is 937 mg/L. The injected CO_2 with purity of 99.99 mol% was from Beijing, China.

Table 2 Compositions of the formation oil

Component	mol%	Component	mol%
CO_2	0.000	nC_4	0.042
N_2	1.859	iC_5	0.026
C_1	28.641	nC_5	0.033
C_2	1.080	C_6	0.066
C_3	0.189	C_{7+}	67.997
iC_4	0.067		
Total	100		

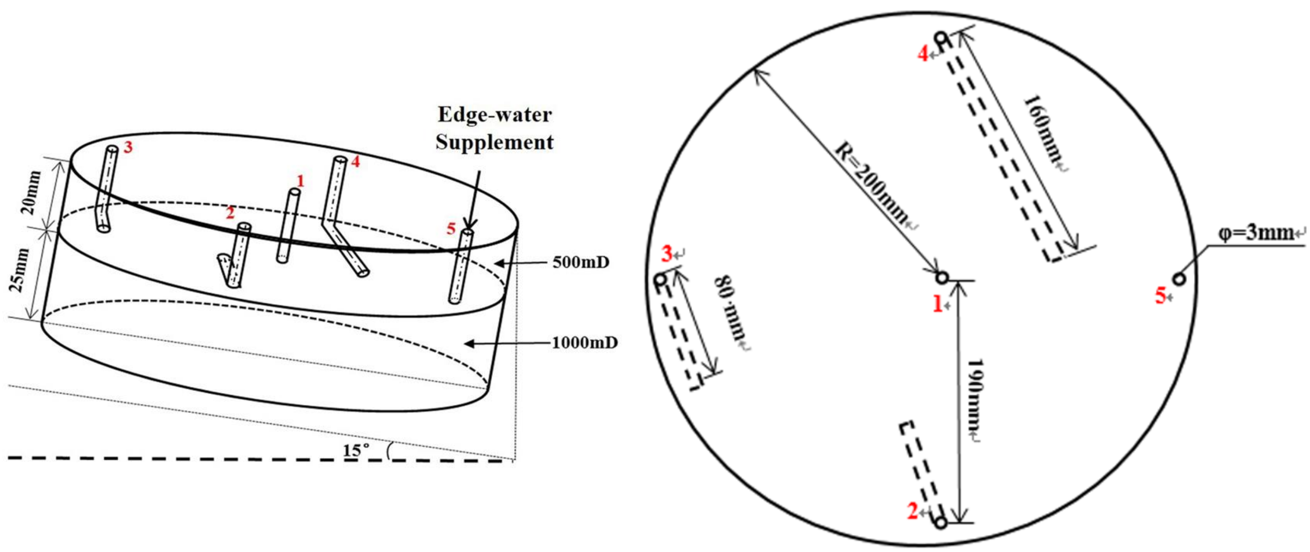
Homogeneous core with a permeability of 500×10^{-3} μm^2, and heterogeneous cores with permeability of 1000/500×10^{-3} μm^2 (The permeability contrast is 2) were utilized in the laboratory experiments. The diameter of 3D physical models is 400 mm and the thickness is 45 mm. The 3D artificial cores were fabricated by quartz sand, clay, resin, solidifying agent and ethyl with certain proportion. The physical parameters of the 3D models are tabulated in Table 3.

Table 3 Physical parameters of 3D models for synergetic CO_2 huff-n-puff

Scenario.	Model	Permeability contrast	Permeability /10^{-3}μm^2	stratigraphic dip	Apparent volume /mL	Pore volume /mL	Porosity /%	Initial oil saturation/%
1	Homogeneous core	1	500	15°	4652	792	17.02	59.32
2	Heterogeneous core	2	1000/500	0°	4753	839	17.65	62.69
3				15°	4505	810	17.98	64.57

Fig.1 is the scheme of 3D physical model. In order to simulate horizontal well group of the model, Well-2, Well-3 and Well-4 were pre-located in the middle of the core during the process of fabricating as shown in Fig.1(a). The horizontal wells were parallel with each other as shown in Fig.1(b), which was similar to the well pattern of actual oil field. The horizon section of Well-2 and Well-3 were 80 mm, and the horizon section of Well-4 was 160 mm, which were isometic with the horizon sections of the wells in the oil field. Well-2, Well-3 and Well-4 were perforated to obtain preferable ability of the whole horizon sections.

Well-5 was a vertical well with a constant water injection pressure to simulate the sufficient edge-water supplement, and Well-1 was a vertical well located in the middle of the model to monitor the formation pressure.



(a) Side view **(b) Top view**

Fig.1. Schematic of 3D physical model

Fig.2 is the picture of 3D physical model with horizontal well group pre-located in the model. Fig.3 is the 3D coreholder (Jiangsu, China) with maximum operation pressure of 15 MPa, and the coreholder can be rotated from 0°to 90°. After the core model was prepared, it was placed in the coreholder to form different stratigraphic dips of the formation. With the existence of stratigraphic dips, three horizontal wells can be located in different tectonic positions: Well-4 located in low tectonic position, Well-2 located in middle tectonic position, and Well-3 located in high tectonic position (As shown in Fig.1(a)). With the horizontal wells located in different tectonic positions of the model, synergetic effect of CO_2 huff-n-puff in edge-water flock-block reservoir can be studied in the laboratory.

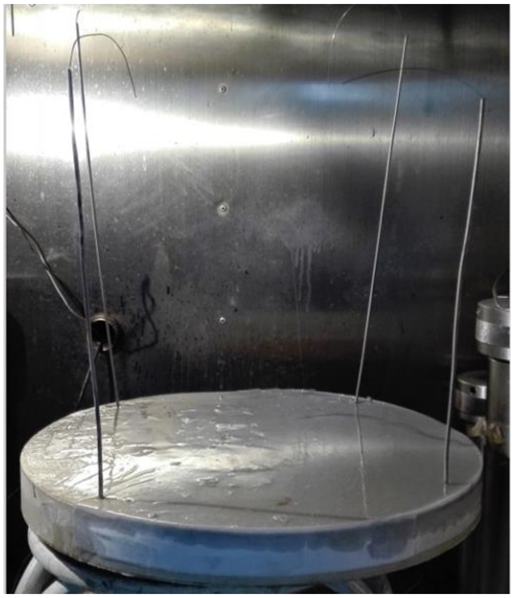


Fig.2. Picture of 3D physical model

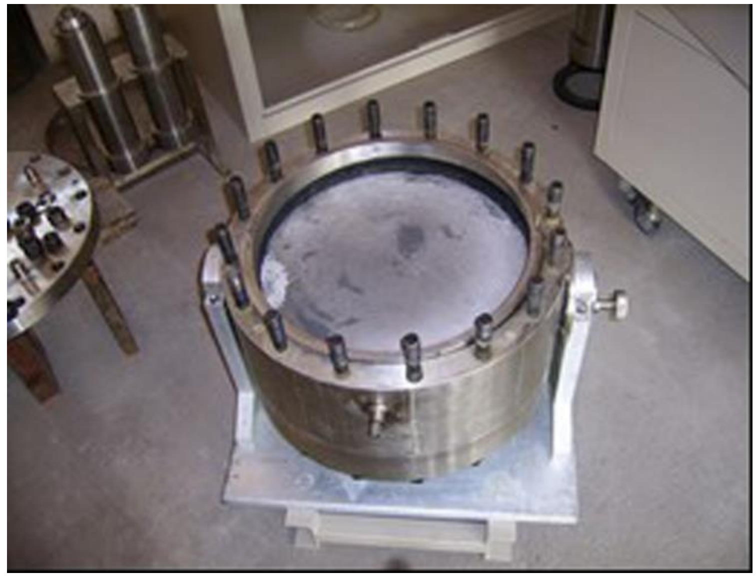


Fig.3 Coreholder of 3D physical model

3.2 Experimental setup

The experimental setup consisted of six sub-systems: injection system, edge-water injection system, displacement system, production system, temperature control system and data acquisition system (As shown in Fig.4). In the injection system, the formation water, formation oil and CO_2 were stored in transfer cylinders and injected into the 3D physical model by a constant pressure and rate pump (HAS-100HSB, Jiangsu, China). In the edge-water injection system, formation water was stored in the transfer cylinder and injected into the 3D physical model through Well-5 by another constant pressure and rate pump. The 3D physical model was placed in the coreholder (As shown in Fig.3), and water was used to provide confining pressure to the coreholder which was usually 2 MPa higher than the injection pressure. In the production system, backpressure regulars (BPRs) were connected with the horizontal wells to control the production pressure. The produced oil and water was recorded by test tubes, while the gas was measured by a gas flow meter (CS200, Beijing, China). The thermostant was used to set the experimental temperature as the reservoir temperature. The formation pressure monitored by Well-1 and the displacement pressure of edge-water were recorded by the data acquisition system.

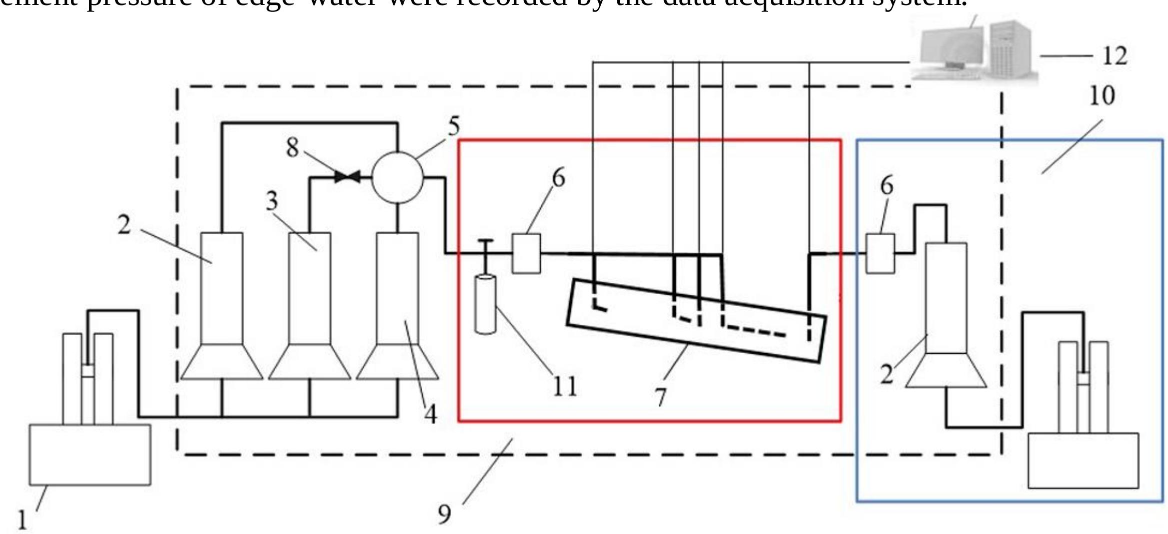


Fig.4 Schematic of experimental setup.

1-Constant pressure and rate pump; 2-Water transfer cylinder; 3-Gas transfer cylinder; 4-Oil transfer cylinder; 5-Six-way valve; 6-Backpressure regulator (BPR); 7-3D coreholder; 8-One-way valve; 9-Thermostat; 10-Edge-water injection system; 11-Test tubes; 12-Data acquision system

3.3 Experimental procedure

3D displacement experiments were designed to study the synergetic CO_2 huff-n-puff with sufficient edge-water supplement in the laboratory. First, homogeneous and heterogenous models were utilized to investigate the factors of heterogeneity on the formation of synergetic effect, then the heterogenous models were placed with dips of 0° and 15° to discuss the influence of stratigraphic dip on the formation of synergetic CO_2 huff-n-puff. The experimental procedures are detailed as follows:

First, 3D physical model and horizontal wells were fabricated and pre-located according to the designing. Then, epoxy resins were coated on the surface of the core to avoid corruption of CO_2. The bulk volume of the core was measured before displacement experiment. The core was firstly evacuated and then saturated with formation water. The porosity was determined as the ratio of brine saturation volume to the bulk volume. Finally, the core was displaced by formation oil to reach the residual water saturation condition. The initial oil saturation was calculated as the ratio of injected oil volume to the pore volume.

The detailed sequence of the experiment is explained as follows. ① The 3D physical model was homogeneous with a stratigraphic dip of 15° in Scenario 1, the model was heterogeneous and horizontally arranged in Scenario 2, and the model was heterogeneous with a stratigraphic dip of 15° in Scenario 3. ② The formation temperature was set as 333.15 K (60℃). The backpressure of horizontal wells (Well-2, Well-3 and Well-4) was set as 10 MPa to maintain the formation pressure and the supercritical condition of CO_2. Edge-water system was connected with 3D model through Well-5 under constant injection pressure of 10.05 MPa to simulate the sufficient edge-water supplement of the flock-block reservoir. ③ Edge-water driving was conducted firstly in the 3D physical model. Well-2, Well-3 and Well-4 were opened when the edge water was injected into the core. The edge-water driving process was terminated when the water cut of Well-4 reached 98%. ④ CO_2 huff-n-puff process was conducted in the 3D model subsequently. First, CO_2 was injected into the core through Well-4 with an injection volume of 0.2PV (Subsurface). Then, Well-2, Well-3 and Well-4 were shut-in for 12 h to reach the dissolving equilibrium of CO_2 and formation oil. ⑤Well-2, Well-3 and Well-4 were opened simultaneously during the CO_2 puff process, and the experiment was terminated when the water cut of Well-4 reached 98% again. During the whole CO_2 huff-n-puff process, Well-5 was maintained open to provide sufficient edge-water supplement. Well-1 was used to monitor the change of formation pressure, and oil production, water production and gas production were measured during the experiments.

4. Results and discussion

4.1 Oil increment by synergetic CO_2 huff-n-puff

The experimental results of CO_2 huff-n-puff process conducted after natural depletion period are shown in Table 4. During the natural depletion period, the oil recovery of edge-water driving in Scenario 1, Scenario 2 and Scenario 3 were 21.33%, 12.01% and 15.39%, respectively, and the oil recovery of homogeneous model with a stratigraphic dip of 15° was the highest. Because of the better formation condition, larger swept area can be achieved with the gravitational differentiation between oil and edge-water. Similarly, the oil recovery of edge-water driving in Scenario 3 reached 15.39% with the gravitational differentiation. While, the oil recovery of edge-water driving in Scenario 2 was the lowest due to serious edge water invasion. For the production of individual well, the oil recovery of Well-4 was the highest, Well-2 was second, and Well-3 was the least. Because Well-4 was nearest to the aquifer, plenty of formation oil can be displaced to the wellbore of Well-4 by the edge-water. One the other hand, the water cut of Well-4 increasing sharply and burst water flooding firstly occurred in Well-4 which seriously affect the development of the block. When the water cut of Well-4 reached 98%, the water cut of Well-2 also reached 90-95%, and the water cut of Well-3 reached 80-85%.

Fig.5 is the incremental oil recovery of CO_2 huff-n-puff process after natural depletion period. After 0.2PV (Subsurface) of CO_2 was injected into the 3D model, 10~15% OOIP can be recovered with the horizontal well group in each scenario under the mechanisms of oil sweeping and viscosity reduction. For the individual well, 6.5-8% OOIP can be recovered through Well-4. And for all the scenarios, the

Table 4 Experimental results of CO_2 huff-n-puff in 3D models

Scenario.	Model				Horizontal well		Oil recovery/%		
	Heterogeneity	Permeability ratio	Permeability /$10^{-3}\mu m^2$	stratigraphic dip	No.	Tectonic position	Edge-water driving	CO_2 huff-n-puff	Total
1	Homogeneous core	1	500	15°	Well-4	/	9.15	6.69	15.84
					Well-2	/	6.35	3.20	9.55
					Well-3	/	5.83	2.73	8.56
					Total	/	21.33	12.62	33.95
2	Heterogeneous core	2	1000/500	0°	Well-4	Low	5.65	8.01	12.66
					Well-2	Middle	3.30	2.20	5.50
					Well-3	High	3.06	1.23	4.29
					Total	/	12.01	11.44	23.45
3				15°	Well-4	Low	6.78	7.86	14.64
					Well-2	Middle	4.43	4.42	8.85
					Well-3	High	4.18	3.54	7.72
					Total	/	15.39	15.82	31.21

formation oil can also be produced through Well-2 and Well-3 unless the gas was only injected through Well-4. This result was consistent with the result of pilot test, which indicated that the synergetic effect indeed existed during CO_2 huff-n-puff in horizontal well group.

The incremental oil recovery of CO_2 huff-n-puff was 15.82% in the heterogeneous model with a stratigraphic dip of 15°, which achieved the best synergetic effect of CO_2 huff-n-puff. The incremental oil recovery of Well-2 and Well-3 in Scenario 3 was 4.42% and 3.54%, respectively, which was also the highest among the three laboratory experiments. After CO_2 was injected into the model through low position well, the remaining oil around middle and high position wells can be effectively displaced by the synergetic effect. And the heterogeneity and stratigraphic dip are advantage for synergetic effect of CO_2 huff-n-puff.

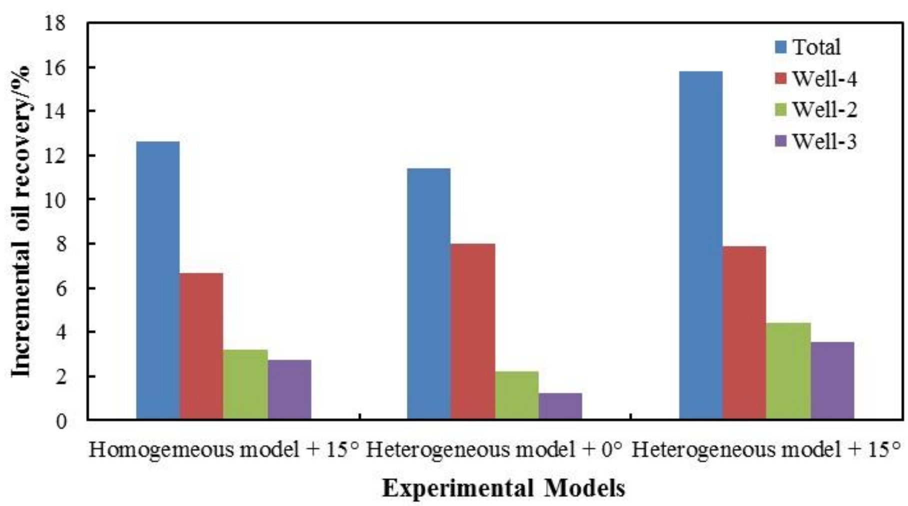


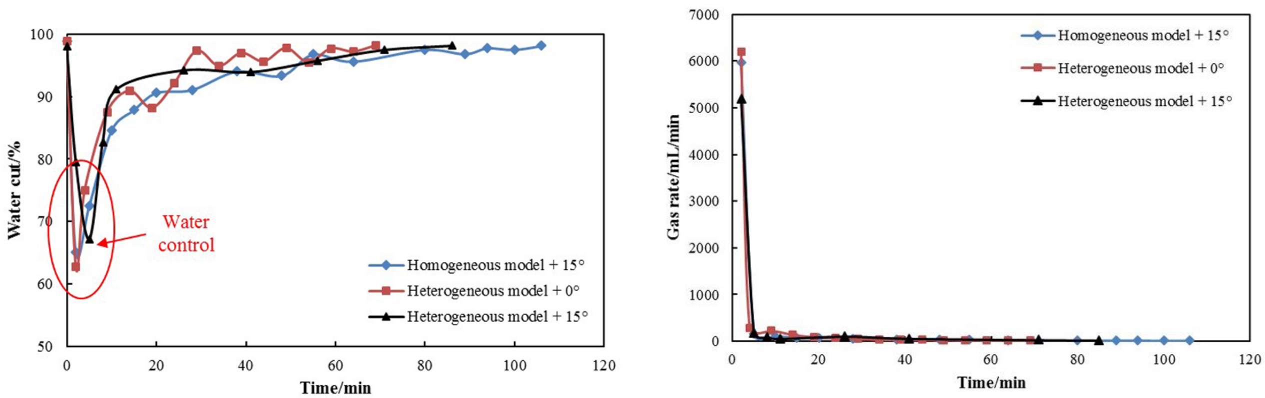
Fig.5 Incremental oil recovery of CO_2 huff-n-puff process

4.2 Synergetic Mechanisms by CO_2 huff-n-puff in horizontal well group

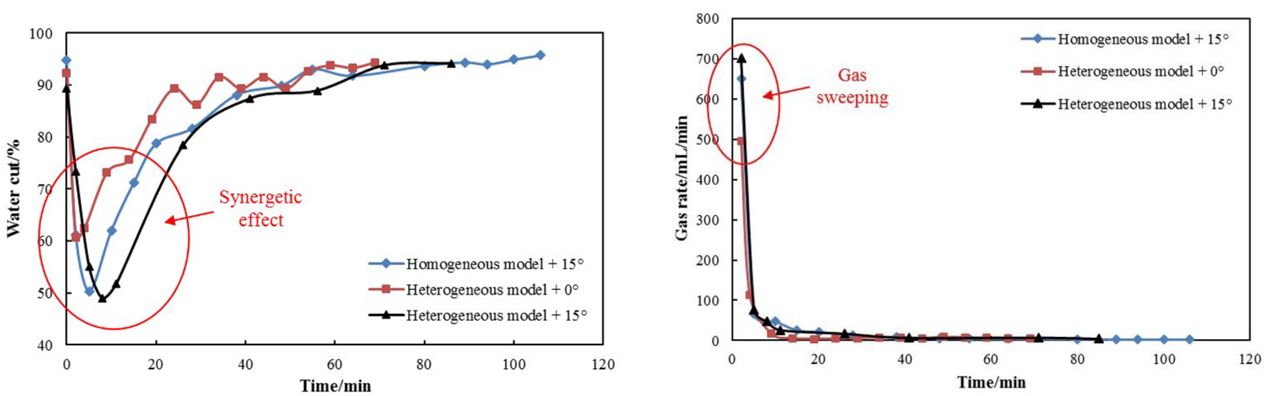
In order to discuss the synergetic mechanisms by CO_2 huff-n-puff in horizontal well group, the water cut and the producing gas rate were further analyzed as shown in Fig.6. For illustration purpose, Well-4 was defined as Operation well, and Well-2 and Well-3 were defined as Responding well. For operation well of Well-4 (As shown in Fig.6(a)), water cut dropped and plenty of gas was produced immediately when the well was opened during CO_2 puff process. The water cut of operation well can be dropped to 60-70%, which indicated that the edge-water was effectively controlled after CO_2 was injected into the model. The water control mechanisms can be explained as follows: (1) As CO_2 was injected into the model, the formation pressure increased from 10.65MPa to 13.75MPa. The formation energy supplement restrained the invading front of edge-water. (2) CO_2 can be partly dissolved into the invasion water near wellbore and reduce the water cut of the operation well.

For responding well of Well-2 (As shown in Fig.6(b)), Synergetic effect can be observed in all the scenarios with the water cut dropped from 90-95% to 50-60% during CO_2 puff process. Plenty of gas was produced immediately when responding well of Well-2 was opened, which indicated that the synergetic effect of CO_2 huff-n-puff was mainly caused by gas sweeping. After CO_2 dissolved with formation oil and edge-water, the injection gas can be swept to the near-wellbore area of Well-2 with enough injection volume of CO_2, and then caused the synergetic effect during CO_2 huff-n-puff process.

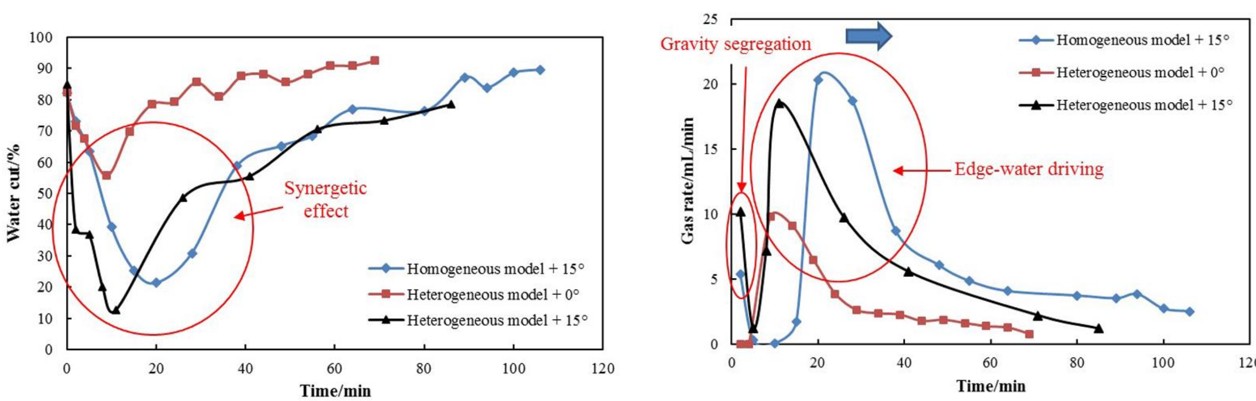
For Responding of Well-3 (Fig.6(c)), synergetic effect was also observed with the water cut dropped and gas produced during CO_2 huff-n-puff process. Unlike the immediate gas production of Well-2, the gas production performance was differential in Responding well of Well-3. In Scenario 1 and Scenario 3



(a) Operation well (Well-4)



(b) Responding well (Well-2)



(b) Responding well (Well-3)

Fig.6 Water cut and producing gas rate of CO_2 huff-n-puff process

with the existence of stratigraphic dip, some gas was produced immediately when Well-3 was opened, while little gas was produced in Scenario 2 with the heterogenous model horizontally placed. This phenomenon can be explained that as the existence of stratigraphic dip, some gas migrated upward with the gravity segregation between formation oil and gas after CO_2 injected through low position well (Well-2). While the producing gas rate of homogeneous model was less than the producing gas rate of heterogeneous model, which means that the heterogeneity is an advantage to accelerate the gas migrating upward.

Unlike the immediate dropping of water cut in Well-2, the water cut of Well-3 reached its minimum after displacement for 10-20 min. Meanwhile, producing gas was also observed as the displacement process, and the gas rate reached its maximum at the same time. After plenty of gas was produced through responding wells at the early stage of CO_2 puff process, about 5-10% of free gas can still be remained inside the 3D model. This part of gas was driven upward by the edge-water, and then formed a CO_2-assisted edge-water driving to displace the interwell oil in-depth reservoir. Compared Scenario 1, Scenario 2 and Scenario 3, the synergetic effect caused by CO_2-assisted edge-water drving was better with a stratigraphic dip. In Scenario 1 and Scenario 3, the injecting CO_2 can migrate upward after enough time for soaking and leave some gas remained inside the model. However, the injection CO_2 was only remained around the near-wellbore areas of Well-2 and Well-3 in Scenario 2 with no gas migration, and most of the gas was produced at the early stage of CO_2 puff process.

With the analysis of production performance of CO_2 huff-n-puff process in horizontal well group, the synergetic effect by CO_2 huff-n-puff can be summarized as follows.

(1) Formation energy supplement for edge water control: The formation energy supplement can restrain the invading front of edge-water and reduce the water cuts of horizontal well group.

(2) Gas sweeping: Gas can be swept to the near-wellbore area of responding well with enough injection volume of CO_2.

(3) Gravity segregation: Gravity segregation can be generated with the existence of stratigraphic dip and heterogeneity.

(4) CO_2-assisted edge-water driving: CO_2-assisted edge-water driving can be formed with the remaining gas and sufficient edge-water supplement to displace the interwell oil in-depth reservoir.

4.3 Numerical simulation of synergetic CO_2 huff-n-puff

In order to further further discuss the synergetic types and injection allocations for CO_2 huff-n-puff in horizontal well group, base reservoir model was built using Eclipse Compositional Simulator. The model was 350m, 200m, 6.6m in the x, y and z dimensions, respectively. The sand body was normal rhythmic with a stratigraphic dip of 15° as shown in Fig.7. Two horizontal wells of P1 and P2 was performed in the model. P1 was located in the low tectonic position of the model, while P2 was located in the high position of the model. The horizontal sections of P1 and P2 were 70 m, and the distance between wells was 70m. The oil viscosity was 39.5 mPa·s, and the initial oil saturation was 0.55. Other parameters of the base reservoir model were summarized in Table 5.

Several numerical simulations of synergetic CO_2 huff-n-puff were conducted of after edge-water driving in the base reservoir model. The synergetic type can be subdivided into single-well synergy and multi-well synergy according to the allocation of CO_2 injection volume. In single-well synergy with Scenario 1 and Scenario 2, 800 t of CO_2 was injected into the model through low position well (P1), and high position well (P2), respectively. In multi-well synergy with Scenario 3, Scenario 4 and Scenario 5, 800 t of CO_2 was injected into the model through low position well (P1) and high position well (P2)

Table 5 Parameters of the base reservoir model

Parameter	Value	Parameter	Value
Reservoir depth (m)	1760	Average porosity	0.26
WOC (m)	1768	Average horizontal permeability ($10^{-3}\mu m^2$)	553
Reservoir temperature (K)	333.15	Permeability variation coefficient	0.5
Initial formation pressure (psi)	2552		

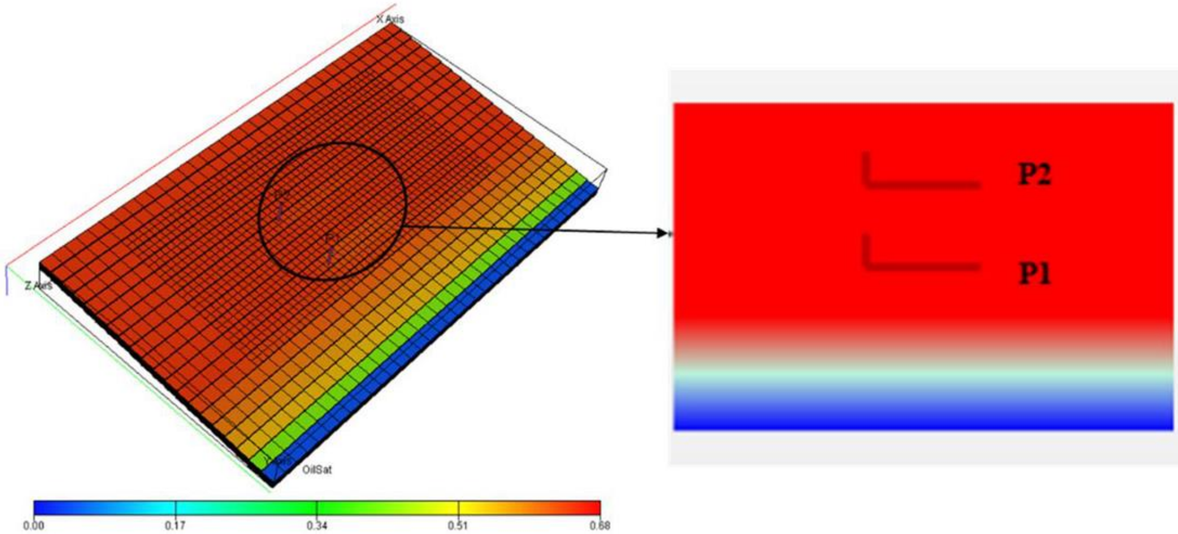


Fig.7 Base reservoir model for synergetic CO_2 huff-n-puff

simultaneously with different gas injection allocation. The soaking time in single-well synergy and multi-well synergy was 50 d.

The numerical results of synergetic CO_2 huff-n-puff are shown in Table 6. In single-well synergy, the incremental oil production of Scenario 1 was higher than that of Scenario 2. In Scenario 1, the edge water can be effectively controlled by energy supplement with CO_2 injected into low position well, and then synergetic effect can be observed with the water cut and oil increment of high position well. The numerical result of Scenario 1 was also in accordance with the 3D experimental results above. Comparatively, less incremental oil was produced with CO_2 injected into high position well in Scenario 2. The injecting gas was mostly utilized to dig the remaining oil in high tectonic position of the reservoir, and less synergetic effect was formed during CO_2 huff-n-puff process. Thus, it is better to inject CO_2 into low tectonic position of the model to strengthen the synergetic effect for enhancing oil recovery in single-well synergy.

Table 6 Numerical results of synergetic CO_2 huff-n-puff in base reservoir model

Scenario	Synergetic Type	Injection Well	Injection Volume (t)	Production of Horizontal Well Group	
				Incremental Oil Production (bbls)	Water Cut Drops (%)
1	Single-well Synergy	Low Position Well	800	4780.4	47.47
2		High Position Well	800	3333.7	20.1
3	Multi-well Synergy	Low Position Well + High Position Well	400 (L) + 400 (H)	5245.9	36.54
4		Low Position Well + High Position Well	100 (L) + 700 (H)	5271.0	29.69
5		Low Position Well + High Position Well	700 (L) + 100 (H)	5767.9	47.47

The numerical results showed that the incremental oil production of multi-well synergy was higher than that of single-well synergy, and the incremental oil production of Scenario 5 was the highest among the multi-well synergy. The injection allcolation can somehow influence the synergetic effect of CO_2 huff-n-puff. In Scenario 5, with 700 t of CO_2 injected into low position well, the edge-water invasion can be controlled, and the synergetic effect can be formed. While with 100 t of CO_2 injected into high position well, the remaining oil in high tectonic position of the reservoir can also be effectively digged out. Thus, the synergetic effect of CO_2 huff-n-puff can be maximumed with proper injection allocation. Scenario 5 illistrated that about 5767.9 bbls oil of the horizontal well group could be recovered with 700 t CO_2 injected into low position well + 100 t CO_2 into high position well, which provided a feasible injection plan for the application of synergetic CO_2 huff-n-puff in the oil field.

5. Conclusion

3D experimental device and base reservoir model were utilized to simulate synergetic CO_2 huff-n-puff in horizontal well group. Through laboratory and numerical simulations of synergetic CO_2 huff-n-puff, some conclusions can be summarized as follows.

(1) Synergetic CO_2 huff-n-puff is a smart cyclic gas injection strategy for the well group, and usually occurres with the gas injected into low tectonic position of the edge-water flock-block reservoir. The drop of water cut and the increment of crude oil can be observed both in the operation well and responding well with synergetic effect of CO_2 huff-n-puff.

(2) The mechanisms of synergetic effect can be concluded as formation energy supplement, gas sweeping, gravity segregation and CO_2-assisted edge-water flooding, and the heterogeneity and stratigraphic dip are advantage for the formation of synergetic CO_2 huff-n-puff.

(3) The synergetic types of CO_2 huff-n-puff can be summarized as single-well synergy and multi-well synergy. For single-well synergy, edge-water invasion can be effectively controlled by energy supplement with CO_2 injected into low position well. For multi-well synergy, better synergetic effect and remaing oil displacement can be achieved after gas injected through different positions of the well group.

(4) About 5767.9 bbls oil of the horizontal well group could be recovered with 700 t CO_2 injected into low position well + 100 t CO_2 into high position well, which can provide a feasible injection plan for the application of synergetic CO_2 huff-n-puff in the oil field.

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