Laboratory Investigation of Sweeping Efficiency By Multiple Horizontal Wells CO_2 huff and Puff in Fault-Block Reservoirs with an Edge Aquifer

Zhixing Wang1,2,3,4, Jirui Hou1,2,3,4, Hongda Hao1,2,5,6, Fenglan Zhao1,2,6,7, Li Yan7,
(1)CUP-CMG Joint Laboratory for Reservoir Simulation, China University of Petroleum (Beijing), Beijing City, China, (2)Basic Theory and Application Research Laboratory for Enhanced Oil Recovery in Low Permeability Oilfield, Key Laboratory of Tertiary Oil Recovery, CNPC, Beijing City, China, (3)Beijing Key Laboratory of Greenhouse Gas Sequestration and Oil Exploitation, Beijing, China, (4)Unconventional Petroleum Research Institute, China University of Petroleum, Beijing, China, (5)China University of Petroleum (Beijing), Beijing, China, (6)Key Laboratory for Greenhouse Gas Sequestration and Oil Exploitation in Beijing, Beijing City, China, (7)Research Institute of Enhanced Oil Recovery, China University of Petroleum (Beijing), Beijing, China,

Abstract

Water coning constrains the effective development of fault-block reservoirs by horizontal wells. CO_2 huff and puff from field cases prove to be effective in water control and oil stimulation. However, gas sweeping efficiency varies due to geological complexity and unclear oil-water interaction. Therefore, CO_2 huff and puff by multiple horizon wells needs to be optimized for a better sweep efficiency. A physical model similar to a fault-block reservoir with edge aquifer and reservoir dip was devised. Three horizontal wells were deployed according to the distance from the aquifer. CO_2 huff and puff experiments were conducted to investigate sweeping results of the selection of injecting well, combination of injection wells within the model. In addition, one numerical model corresponding to the physical one was built and numerical experiments were carried out to quantify the gas sweeping efficiency. The simulation results show that the sweeping effect decreased with the increase in the distance from the aquifer as CO_2 was injected from one horizontal well. Furthermore, when two optimized horizontal wells huffed the similar amount of CO_2, gas sweeping efficiency improved: A higher drop in water cut (34.26% to 33.53%), more oil recovery increase (15.38% to 17.59%), and a lager gas sweeping volume (33.56% to 24.66%) were obtained in the simulation experiments. It was concluded that CO_2 sweeping efficiency could be further improved within the same gas volume by horizontal wells optimization. Both physical and numerical conceptional model of fault-block reservoir was devised. And the improved CO_2 sweeping efficiency by multiple horizontal wells CO_2 huff and puff offers theoretical reference for field application.

Introduction

Water cresting from horizontal wells caused by aquifers in the bottom and at the edge of the reservoirs constrains the effective development[1-3]. As a result, water cut was hovering at high rate, and well productivity was poor. Chemical methods like conformance control by improving the permeability near the well bore calls for cautious plan for the potential environmental problem and economical cost. Gas injection is one of the oldest methods used by engineers to improve oil recovery, and its application has been increased recently. And CO_2-EOR has two major advantages: (1) additional hydrocarbon recovery that promotes energy independence and (2) CO_2 storage to reduce atmospheric emissions of CO_2.

CO_2 huff and puff has been studied for oil stimulation and coning control both in field and lab for over 60 years. D. H. Stright et al[4] invested the results of one pilot test in reservoirs with bottom and edge aquifers with numerical methods. And the simulation results showed the oil rate increased and water oil ratio (WOR) dropped. A. F.S. Palmer [5] applied the optimized huff and puff parameters to one water flooded well in West Cote Blanche Bay reservoir, and the effective time lasted over two years. M. R. Simpson [6] pointed the uniform dispersion in the formation made CO_2 huff and puff economic in both lowering water cut and boosting oil production. S. Vega Sankur et al[7] invested the PVT properties of CO_2-heavy oil system, and there was 16% in oil expansion and 45% in viscosity reduction. Haskin and Alston[8] summarized the results of 28 CO_2 huff and puff projects in Texas, and pointed out that working parameters like CO_2 slugs and soaking time should be optimized according to the oil viscosity. Charles Bardon et al[9] discussed the mechanisms of gravity drainage, CO_2 solubility in brine, imbibition, retention during the CO_2 huff and puff, and explained the process of oil saturation reduction due to interfacial reduction or wettability alteration by CO_2.

For the purpose of this paper, sweeping efficiency of CO_2 huff and puff by multiple horizontal wells in a 3D model with edge aquifers was studied on the aspect of different injection methods. Four CO_2 huff and puff experiments were conducted to investigate the CO_2 sweeping pattern. And three numerical experiments corresponding to model corresponding to the physical experiments were carried out to roughly quantify the gas and oil distribution across the radius model.

Experimental materials and methods

Materials

The crude oil used in the experiment was obtained from C2 block in the Jidong Oilfield, is the mixture of reservoir crude oil with kerosene. And the oil viscosity is 189mPa·s under the reservoir condition(60 ℃, 16.4 MPa). Brine of the edge aquifers was collected from the production well with a salinity of 937mg/L, $NaHCO_3$ type. The CO_2 was from the Jinggao Gas limited company with a purity of 99.9%.

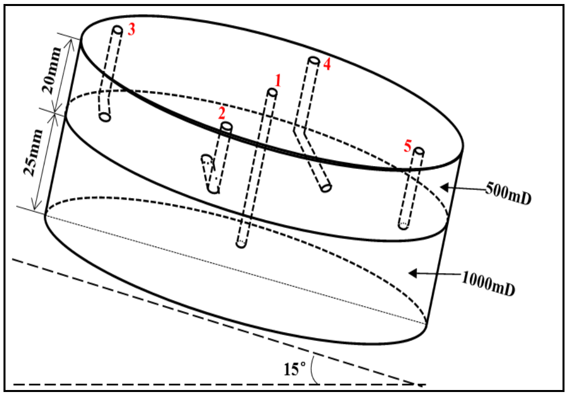
Physical model

The 3D radius model was obtained by outcrop sand cemented by epoxy and clay minerals. The diameter of the 3D model is 400mm, and the thickness is 45mm. There are two layers with different permeabilities, $500\times10^{-3}\mu m^2$ of the upper layer with 20mm thick and $1000\times10^{-3}\mu m^2$ of the sublayer with 25mm thick. In order to reduce error from the model permeability, 5 core samples were made by the same method along with the 3D model. Core properties are listed in **Table 1**.

Table 1 Summary of core properties for the experiments of CO_2 huff and puff in the 3D models

Case NO.	Well(s) CO_2 injected	bulk volume, cm^3	pore volume, cm^3	porosity, %	Oil saturation, %
1	Well 4	4552	842	18.49	75.06
2	Well 2+ Well 4	4910	856	17.43	68.46
3	Well 3 + Well 4	4750	876	18.44	71.35
4	Well 2+Well 3 + Well 4	4505	810	17.98	64.56

There are 5 simulated wells distributed in the 3D model (**Figure 1**). Well 1 is located in the center as a monitoring well, buried 45mm deep within the model. Well 5 is on the edge of the model, severing as an edge aquifer by injecting brine under certain pressure through the ISCO pump. The other three are horizontal wells as one production unit, buried in the middle of the permeability layers with horizontal length of 8cm (Well 2 & Well 3) and 16cm (Well 4). And there are micropores (0.1mm in diameter) drilled in the surface of the simulated wells as perforation holes. The 3D model is tilted with 15° to simulate the reservoir dip during the whole process. Therefore, the three horizontal wells can be distinguished by the geological portion, Well 3 as top, Well 2 as middle, and Well 4 as bottom.



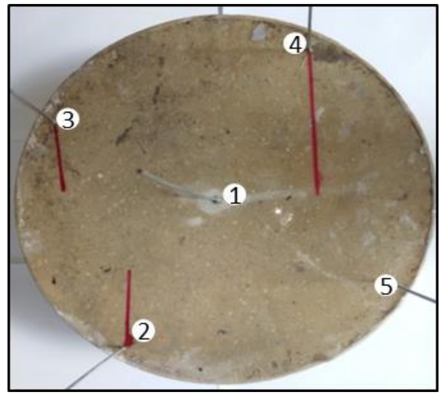


Figure 1.a Conceptional model **Figure 1.b** Actual model

Figure 1 Demonstration of conceptional and actual physical model(red lines demonstrate)

Apparatus

The CO_2 huff and puff by multiple horizontal wells schematically shown in Fig.2 was utilized in the experiments. A radius core holder specifically designed to the 3D model size with an inner diameter of 45cm diameter and depth of 10cm was used as a radius core holder for the CO_2 huff and puff experiments. This special core holder could sustain pressures up to 20MPa and temperature to 120℃. There are two high-pressure pumps (Model 100DX, Teledyne Technologies) working separately to pressurize the CO_2 (1 in Fig.2) and control the flow rate of the edge aquifer (5 in Fig.2). Pressures in the radius core holder were measured using pressure transducers (JYB-KO-H, Beijing ColliHigh sensing technology co., LTD). The produced gas and liquid were separated and measured by gas flowmeters (LF420-S, Laifeng Scientific Technology co., LTD) and graduated test tube. The aquifer injection system shown 7 in **Figure2** contains three main parts: high pressure pump, intermediate cylinder(brine) and back pressure regulator.

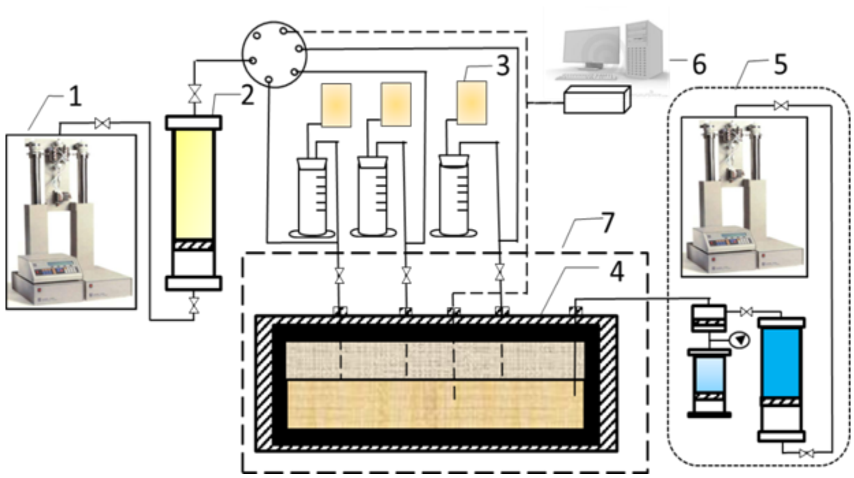


Figure 2 Experimental apparatus of CO_2 huff and puff by multiple horizontal wells

1. high-pressure pump (Model 100DX, Teledyne Technologies), 2. CO_2 cylinder, 3. Production measurement system, 4. HTHP radius core holder, 5. Edge aquifer injection system, 6. Data process system, 7. Air bath.

gas injection methods

There are four CO_2 injection strategies in this study: ① CO_2 injected from one horizontal well (the bottom, Well 4), ② CO_2 injected from two horizontal wells (the top, Well 3 and the bottom, Well 4) ③ CO_2 injected from two horizontal wells (the middle, Well 2 and the bottom, Well 4) ④ CO_2 injected from all horizontal wells. And CO_2 was injected simultaneously to the horizontal wells.

Calculation and measurement of the CO_2 volume

As introduced in the previous section, the CO_2 volume can be calculated by the density changes in a constant volume cylinder with a movable piston before and after injection at the constant temperature. CO_2 equation of state (EOS) in the density form is below,

$$PM_{CO_2} = z\rho_{CO_2}RT \tag{1}$$

The density difference before and after CO_2 can be described,

$$\Delta\rho=\rho_1 - \rho_2=\left(\frac{P_1}{z_1} - \frac{P_2}{z_2}\right)\frac{M_{CO_2}}{RT} \tag{2}$$

The cylinder volume is 1000 cm^3 under this experiment condition, then the mass of the injected CO_2 can be calculated. Additionally, the volume under standard and experimental condition can be calculated by the CO_2 EOS in mass form (Eq. 3). Tab.3 summarized the gas injection volume under

$$PV = z\frac{m_{CO_2}}{M_{CO_2}}RT \tag{3}$$

Table 2 injected and produced CO_2 volume of different injection methods

Model NO.	temperature, K	cylineder pressure, MPa		density, g/cm^3		injected volume	
		before	after	before	after	SC, cm^3	EC, PV
1	333.15	5.75008	5.42253	0.11793	0.10912	4876.79	0.05361
2	333.15	5.85659	5.52253	0.12087	0.11177	5037.32	0.05447
3	333.15	5.85209	5.51253	0.12075	0.11151	5114.81	0.05405
4	333.15	5.84608	5.55111	0.12058	0.11254	4450.55	0.05086

*SC referred to the standard condition, 273.15K, 0.1MPa

**EC referred to the experimental condition, 333.15K, 7.5Mpa

Results and discussions

Physical Experiments

Table 2 summarized the overall results of different CO_2 injection methods. The oil recovery by water flooding from the edge aquifers were no more than 16%, more than 84% oil remained within the model. While the overall water cut from the three horizontal wells were over 90% percent, water coning in the horizontal wells constrained the well.

From the aspect of water coning control, the overall water cut decreased after the model soaked up CO_2 from different wells. Furthermore, the results differed due to CO_2 injection methods. For case 1, Well 4 in the vicinity of edge aquifer was selected for control water coning, and the water cut dropped

33.53% accordingly. However, the drop of water cut became less significant in Case 3 (CO_2 injected from Well 3) by increasing sweeping volume in high portion and Case 4 (CO_2 injected from all horizontal wells) by evenly distributed the injected CO_2. Consequently, the lowest drop was observed in Case 2, when CO_2 was injected from Well 4 and Well 2 simultaneously. For the supplemented CO_2 covered more of the water flooded area than the other injection methods.

Table 3 water control results of different CO_2 injection schemes

Case NO.	water cut, %			invasion volume*/PV	recovery factor, %	
	initial	lowest	Overall decrease		edge water	CO_2+edge water
1	93.36	59.83	33.53	0.92	15.40	15.38
2	90.93	56.77	34.16	0.87	15.90	17.49
3	94.33	64.67	29.66	0.78	15.71	16.56
4	94.16	65.08	29.08	0.76	15.62	17.34

*** Edge water invasion volume was measured by pore volume (PV) as the water cut reached 90%.**

Oil production was also stimulated as a result of CO_2 injection and the subsequent edge water flooding. Viscosity reduction and volume expansion due to CO_2 solution improved the oil mobility. Detailed increased oil recovery was demonstrated in **Figure 3**. For Well 4, located in the lower part of the model, increased oil factor declined with the increase of injection wells, for the energy supplied by CO_2 was desegregated across the model. And for Well 2, which was located in the middle of the model, the increased oil recovery maintained around 6%, because CO_2 from the lower part migrated upward and swept the area due to density difference. For Well 3 in the high portion of the model, oil recovery increased from 4.32% in Case 1 to 7.64% in Case 4. One contribution was the effect of gravity segregation during soaking period, CO_2 accumulated in the upper part of the model, thus forming a secondary gas tap. The other reason was the relatively high oil saturation near wellbore compared to the other two wells, which were experiencing severe water coning by the edge aquifer.

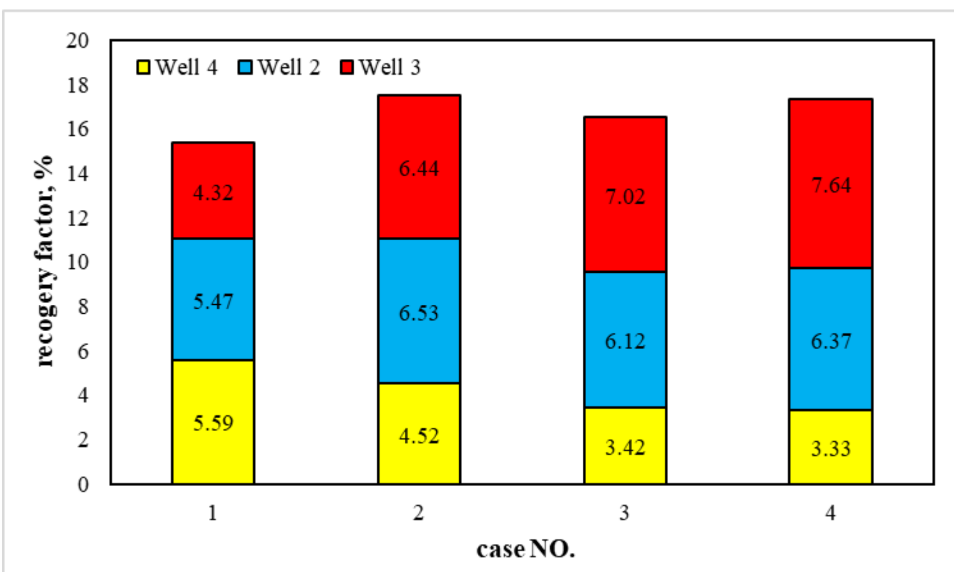


Figure 3 Oil Recovery comparison of different CO_2 methods

Numerical simulation

Gas saturation distribution after CO_2 injection and soak periods in the radius model were to compared to further present the gas sweeping efficiency of the different injection methods. Gas saturation profile of layer3 and side view after CO_2 injection were compared, which represented the gas distribution horizontally and vertically. When CO_2 was injected from Well 4, gas migrated upward near Well 3 and Well 2 (**Figure 4.a**), and downward to the edge aquifer (**Figure 4.b**). Contrary to SAGD, the gas moved to the upper position due to low density, while downward similar to SAGD since the oil density increased due to the dissolution of CO_2. Therefore, the CO_2 swept 57.91% of the layer 3 with 1002.58 cm^3 volume. When CO_2 was injected from Well 4 and Well 2, the sweeping efficiency increased to 59.64%, and the CO_2 migrated near the Well 3, which was not huff CO_2. However, the gravity drainage effect drop down since the CO_2 swept less edge aquifer areas, even though the sweeping efficiency reached 63.86%.

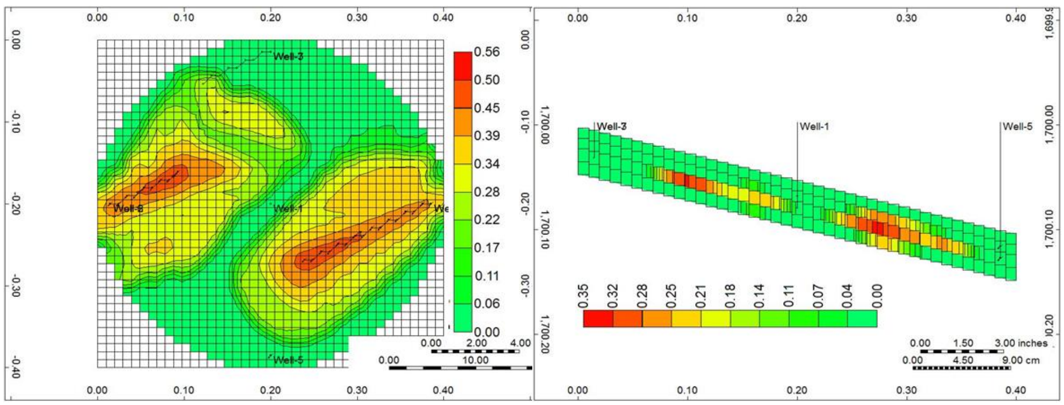


Figure 4.a After gas injection in layer3 **Figure 4.b** After gas injection from side view

Figure 4 Gas saturation distribution during soak period in gas injection from W4 and W2

Furthermore, gas sweeping efficiency of the whole radius model was compared. For case 1, namely CO_2 was injected from Well 4, the lower part of the model, the CO_2 sweeping volume was 1461.04 cm^3 with 24.66% sweeping efficiency; for case 2, when CO_2 was injected from Well 4 and Well 2 simultaneously, CO_2 sweeping volume and sweeping efficiency increased 527.03 cm^3 and 8.90% respectively compared to those of the case 1; and for case 4, when CO_2 was injected from all the three horizontal wells simultaneously, there was a less obvious increase in gas sweeping capacity. Therefore, increasing horizontal wells could achieve a higher gas sweeping volume and efficiency. Since the dissolution of CO_2 into the reservoir liquids, there was a decrease in gas saturation profiles in the model after the same soaking period. Moreover, the existence of the edge aquifer required would the maintenance of reservoir pressure to constrain the coning effect. Therefore, there should be the balance between the sweeping efficiency before and after the soak period, for Case 2, when CO_2 was injected from Well 4 and Well 2 simultaneously, there was still 1609.73 cm^3 sweeping volume across the radius model, top of all the three cases.

Table 4 Summary of sweeping volume in different gas injection patterns

Model NO.	Well(s) CO_2 injected	sweeping volume, cm^3		sweeping efficiency, %	
		after injection	after soak	after injection	after soak
1	W4	1461.04	1124.9	24.66	18.99
2	W2+ W4	1988.07	1609.73	33.56	27.17
3	W2+W3 + W4	1990.65	1576.58	33.60	26.61

Oil saturation distribution of Case 2 was studied in this part. After CO_2 was injected from Well 4 and Well 2, oil saturation varied from 12% near the well bore area to 48% in the further bore zones, corresponding to the gas saturation distribution (**Figure 4.a**), since CO_2 replaced the pore space of oil, which was displaced far from the injection well (**Figure 5.c**). More interestingly, there was a belt with high oi saturation (up to 60%) between Well 2 and Well 4(**Figure 5.a**). CO_2 could not sweep every corner within the limited volume. After the soak period, oil saturation near the horizontal wells recovered (**Figure 5.b**) to 72%, the highest across the radius model due to the gravity drainage and CO_2 solution. Moreover, oil saturation increased gradually from the edge aquifer to the horizontal wells vertically (**Figure 5.d**). The cooperation of supplied CO_2 and innate edge water redistributed oil vertically.

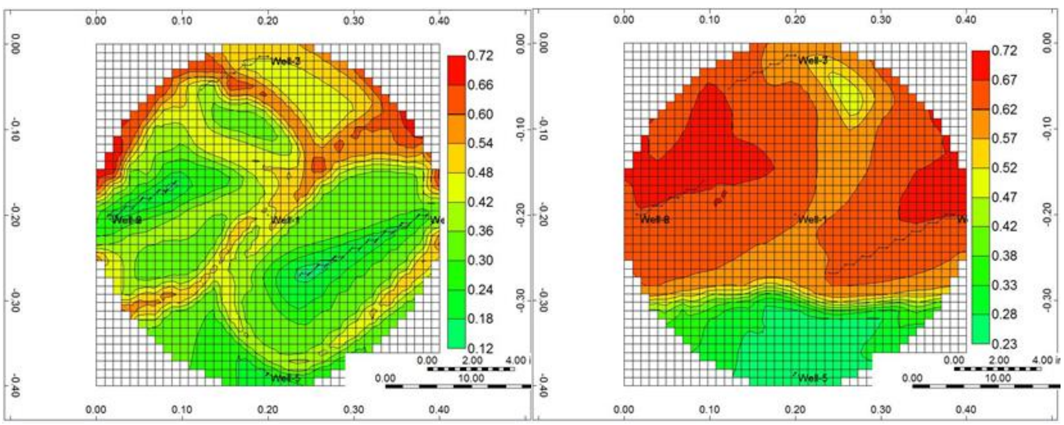


Figure 5.a After gas injection in layer3 **Figure 5.b** After soak in layer3

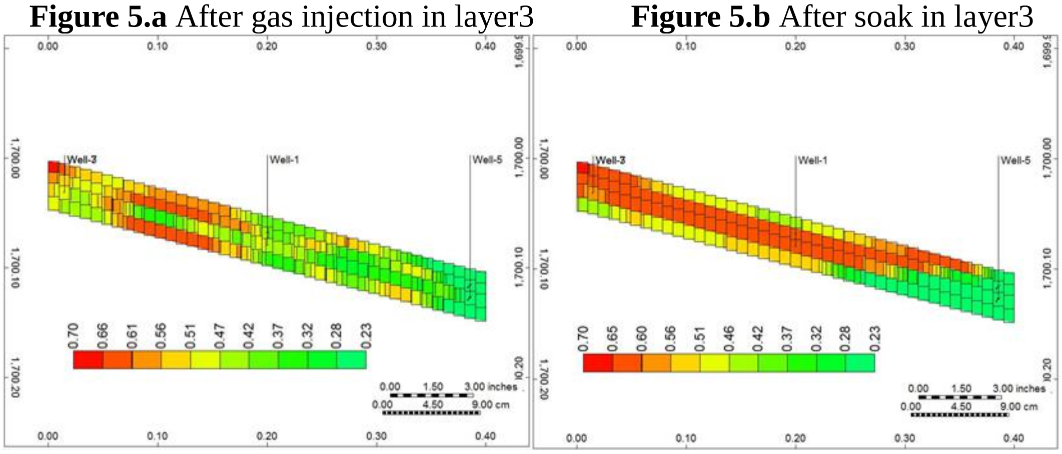


Figure 5.c After gas injection from side view **Figure 5.d** After soak from side view

Figure 5 Oil saturation distribution during soak period in gas injection from W4 and W2

Conclusion

Both physical and numerical experiments have been carried out to study the CO_2 sweeping efficiency within the 3D model with edge aquifer by different injection methods, and the optimized CO_2 injection configuration were discussed. The conclusions were as follows:

(1) CO_2 entered the water flooded pores and expanded the oil, draining away water from the wellbore. And CO_2 huff and puff by multiple horizontal wells enhanced the water drainage effect. Therefore, overall water cut could be reduced by over 20% under this condition and water cresting or coning by edge aquifer can be suppressed to some extent.

(2) The CO_2 huff and puff from multiple horizontal wells enhanced oil mobility, further more the oil recovery. A secondary gas tap formed as the CO_2 was injected from both lower and middle horizontal wells of the radius model, making a high sweeping volume and sweeping efficiency under this condition.

(3) The injection of CO_2 into the multiple horizontal wells should be distributed carefully for a better result in both conning control and oil stimulation. For the given well configuration, there should be at least two horizontal wells for CO_2 injection, one should be close to edge aquifer for coning control, and others should be located in the areas with relatively high oil saturation.

Reference

1 P. Permadi, R. L. Lee, and R. S. T. Kartoatmodjo, “Behavior of water cresting under horizontal well,” SPE30374, 1995.

2 Q. Jiang and R. M. Butler, “Experimental and numerical modelling of bottom water coning to a horizontal well,” Journal of Canadian Petroleum Technology, vol. 37, no. 10, pp. 82 – 91, 1998.

3 S Huang, B Zeng, F Zhao et al. Water Breakthrough Shape Description of Horizontal Wells in Bottom-Water Reservoir, Mathematical Problems in Engineering, vol. 2014, article ID 460896, .https://doi.org/10.1155/2014/460896.

4 S.G. Sayegh, B.B. Maini. Laboratory evaluation of the CO_2 huff-n-puff process for heavy oil reservoirs[J]. 1984, PETSOC-84-03-02.

5 M. Mutailipu, Y. Liu, L. Jiang et al. Measurement and estimation of CO_2–brine interfacial tension and rock wettability under CO_2 sub- and super-critical conditions[J]. Journal of Colloid and Interface Science, 2019: 534, 605-617.

6 H Li, S Zhen, D Yang. Enhanced Swelling Effect and Viscosity Reduction of Solvents-CO_2-Heavy Oil Systems [J]. SPE Journal, 2013,18 (4): 695-707.

7 D. H. Stright, Jr, K. Aziz, A. Se!tari, F. E. Starratt. Carbon dioxide injection into bottom-water, undersaturated viscous oil reservoirs [J]. Journal of Petroleum Technology, October, 1977: 1248-1258.

8 F.S, Palmer, R.W. Landry, S. Sou-Mikael. Design and Implementation of Immiscible Carbon Dioxide Displacement Projects (CO_2 Huff-Puff) in South Louisiana. SPE 15497. Presented at the 61st Annual Technical Conference and Exhibition of the society of Petroleum Engineers held in New Orleans, October 5-S, 1986.

9 Marcia Reeves Simpson. The CO_2 Huff 'n' Puff Process in a Bottomwater-Drive Reservoir. SPE-16720-PA, Journal of Petroleum Technology, July 1988: 887-893.