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Performance Control Methods Applied in Heterogeneous Reservoirs for Improving CO_2 flooding Performance

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Abstract

CO_2-EOR is an effective technology for reducing CO_2 emissions while enhancing oil recovery in ultra-low permeability reservoir, which has been performed in Shengli Oil Field, China since 2013 with cumulative CO_2 injection of 12588 t by 2016. However, the area heterogeneity of reservoir resulted in serious gas channeling and poor production performance. Performance control methods including sweeping area regulation, differential pressure control and real-time producing regulation were proposed to enlarge sweeping area and improve CO_2 utilization in areal heterogenous reservoir. 3D physical models of areal heterogeneity and five-spot pattern were utilized in the laboratory. Conventional CO_2 flooding, sweeping area regulation, differential production pressure control and real-time producing regulation were conducted respectively in the 3D models, and the flooding efficiency was evaluated through oil recovery increments and changes of performance curves. Corescale numerical modeling was also built to study the profile improvements of CO_2 flooding by the performance control methods.

Experimental and numerical simulation results showed that CO_2 was displaced unevenly in the areal heterogeneous reservoir, leaving plenty of oil remained in the relatively high and relatively low permeability area. The oil recovery of CO_2 flooding in areal heterogenous reservoir can be doubled by performance control methods of sweeping area regulation, differential pressure control or real-time producing regulation. The remaining oil in relatively low permeability area can be effectively displaced by sweeping area regulation, while both larger sweeping area and better CO_2 flooding profile can be achieved by differential pressure control and real-time producing regulation. Higher productivity of individual well can be obtained in the early and middle stage of CO_2 flooding by differential pressure control, while similar oil & gas production performance and longer displacement period of CO_2 injection can be achieved by real-time producing regulation. The performance improvement of CO_2 flooding by performance control methods provided a feasible technical strategy for enhancing oil recovery of areal heterogeneous reservoir in the oil field under the condition of a lower oil price.

Keywords: low permeability reservoir; CO_2 flooding; areal heterogeneity; performance control; sweeping area

1 Introduction

CO_2 flooding is considered to be a promising and effective process for enhancing oil recovery (CO_2-EOR) because it can not only increase oil production, but also reduce greenhouse gas emissions by sequestrating CO_2 in reservoirs. Field applications present CO_2 flooding can enhance oil recovery by 8-15% (Pyo et al., 2003; Bachu and Shaw, 2004). However, when CO_2 was injected into the formation, flooding performance was commonly affected by reservoir heterogeneity, and left large amount of oil remained in the reservoirs. Therefore, it is of great importance to improve CO_2 flooding performance in the heterogeneous reservoirs. Previous studies have been conducted for the purpose of maximizing the sweep efficiency of CO_2 flooding with different methods. Malik and Islam (2000) have reported that horizontal injection wells have proved to be efficient for CO_2 flooding processes to improve oil recovery and increase the CO_2 storage in the Weyburn Field of Canada. Shayeqi et al. (1996) have shown that CO_2 injection followed by N_2 slug could enhance oil sweep efficiency and oil recovery in the core flooding experiments. CO_2 water alternating gas (WAG) flooding is considered to be an effective method to improve sweep efficiency in both laboratory experiments and field pilot tests (Christensen et al.,1998; Heeremans et al., 2006; Elfeel et al., 2013a). The injected gas can enhance microscopic displacement efficiency, and the injected water can enhance the macroscopic sweep efficiency. However, the properties of formation fluids and reservoir conditions limit the wide application of WAG flooding (Dijke et al.,2006; Elfeel et al., 2013b). The modified WAGs, such as surfactant alternating gas (SAG) flooding and foam assisted water alternating gas (FAWAG) flooding, have been purposed to expand gas production time during CO_2 flooding (Spirov et al.,2012; Salehi et al.,2014). The utilize of foam can further reduce gas mobility, and then increase sweep efficiency and alleviate the effect of heterogeneity during CO_2 injection, however, the foam stability is seriously affect with the presence of crude oil (Falls et al.,1989; Farajzadeh et al., 2010). Recently, Telmadarreie et al. (2016) has reported that microbubbles of CO_2 with high performance injectivity demonstrated a great potential in enhancing oil recovery in heterogeneous porous media. Zhao et al. (2015) has proposed a profile control method by the reaction products between ethylenediamine and CO_2, and Hao et al. (2016) proposed a two-stage gas channeling control method by high-strength gel and ethylenediamine to improve CO_2 flooding efficiency in ultra-low permeability fractured reservoirs.

As described above, the displacement efficiency can be greatly improved with the utilize of chemical agents during CO_2 flooding, while economic and effective methods for enhancing oil recovery still need to be evolved under the condition of a lower oil price. CO_2 flooding has been performed in Shengli Oil Field, China since 2013 with cumulative CO_2 injection of 12588t by 2016. After serious gas channeling and poor production performance, performance control methods including sweeping area regulation, differential production pressure control and real-time producing regulation are introduced to improve the performance of CO_2 flooding in areal heterogeneous reservoir through 3D experimental and corescale numerical simulations.

2 Experiments

2.1 Materials

The oil sample and formation water were collected from one block of Shengli Oil Field, China. The density of the formation oil is 0.7463 g/cm^3, the viscosity is 1.20 mPa·s, and the gas/oil ratio is 45.6 m^3/m^3. The oil sample mainly contains light or medium components, and the minimum miscible pressure (MMP) measured by slim tube test is 31.6 MPa under the formation conditions (44.87 MPa, 60 °C). The salinity of the formation water is 29884 mg/L and the water type is $CaCl_2$. The injected CO_2 with purity of 99.99 mol% is from Beijing, China.

The 3D heterogeneous models used in the experiments were artificial fabricated by quartz sand, clay and proxy resin. The diameter of the physical model is 400mm, and the thickness is 45mm (As shown in Fig.1). The model was areal heterogeneous with relatively high permeability of $50\times10^{-3}\mu m^2$, and relatively low permeability of $10\times10^{-3}\mu m^2$. An injection-production unit of 5-spot pattern was designed in the 3D physical model. CO_2 injection well (I-1) was located in the center of the model, three production wells (P-1, P-2 and P-3) in relatively high permeability area, and one production well (P-4) in relatively low permeability area. The well spacing between injector and producer was 190mm. Fig.2 is the coreholder of 3D physical model (Jiangsu, China) with maximum operation pressure of 15MPa.

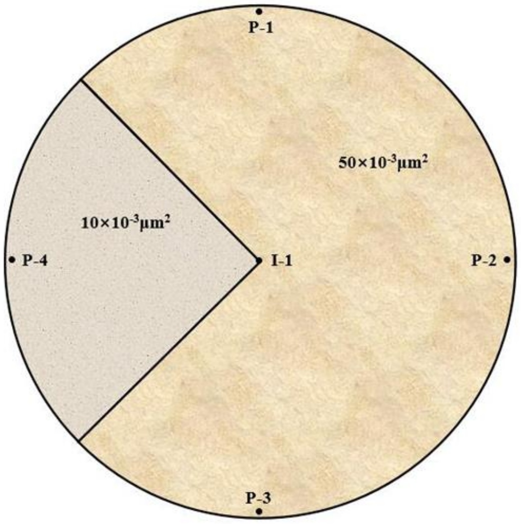


Fig.1 Picture of 3D physical model with areal heterogeneity

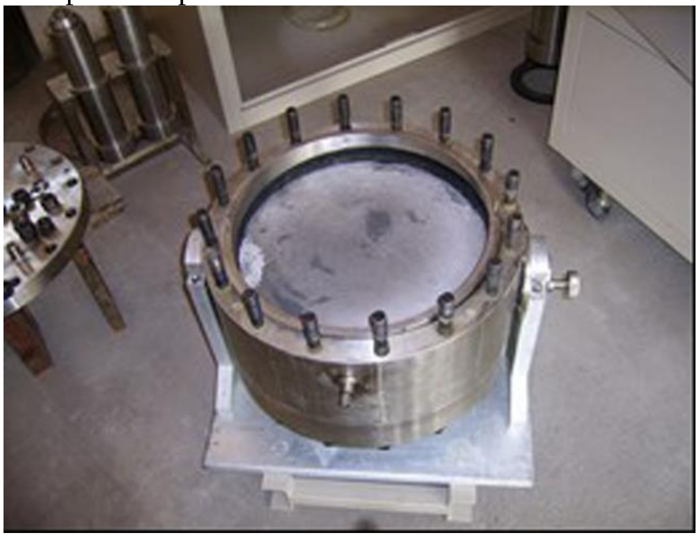


Fig.2 Corehorder of 3D physical model

2.2 Experimental setup

The experimental setup consisted of five sub-systems: injection system, displacement system, production system, temperature control system and data acquisition system (As shown in Fig.3). In the injection system, the formation water, formation oil and CO_2 were stored in transfer cylinders and then injected into the core sample by a constant pressure and rate pump (HAS-100HSB, Jiangsu, China). The injection rate of CO_2 was controlled by a gas flow meter (D07-11C, Beijing, China). 3D heterogeneous models were placed in the 3D radial flow coreholder in the displacement system. In the production system, backpressure regulators (BPRs) were used to control the production pressure. The produced oil was recorded by graduated tubes, and the gas was measured by gas flow meters (CS200, Beijing, China). The thermostat was used to set the experimental temperature as the reservoir temperature, and the displacement pressure was recorded by the data acquisition system.

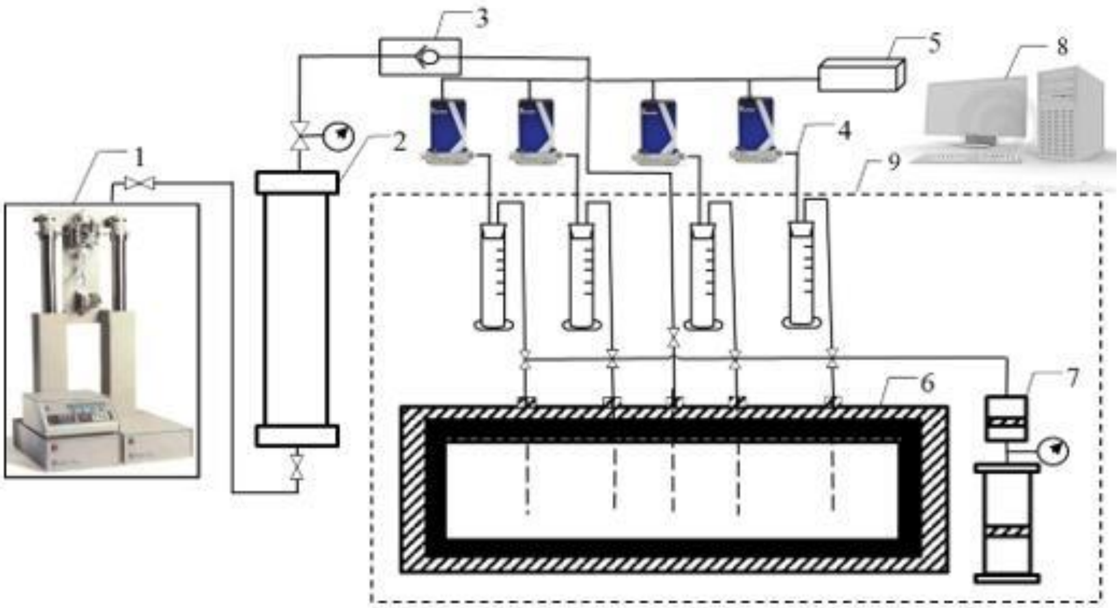


Fig.3 Schematic of experimental setup.

1-Constant pressure and rate pump; 2-Transfer cylinder; 3-One-way valve; 4-Gas-oil separators; 5-Gas flow meters; 6-Radial flow coreholder; 7-Backpressure regulators (BPRs); 8-Data acquisition system; 9-Thermostat.

2.3 Experimental procedure

Several 3D displacement experiments were designed to improve the performance of CO_2 flooding by performance control methods in the laboratory, and the experimental procedures are detailed as follows:

First, the 3D physical model and the 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. The permeability of the core was measured by changing water injection rate from 0.1 to 0.3 mL/min. Subsequently, the core was displaced by formation oil to reach the residual water saturation condition. The initial oil saturation was calculated as the ratio of saturated oil volume to the pore volume.

In conventional CO_2 flooding experiment, gas was injected into 3D physical model without any performance control method during the whole experimental process. The detailed sequence is explained as follows. ① The 3D physical model with areal heterogeneity was placed into 3D coreholder, and the formation temperature was set as 60℃. ② Same production pressure of P-1, P-2, P-3 and P-4 was set as 8 MPa by BPRs to maintain the formation pressure and the supercritical condition of CO_2. ③ Conventional CO_2 flooding was conducted by injecting CO_2 through I-1, and the injection rate was set as 1.5 mL/min. All the producers with the same backpressure were opened simultaneously. ④ The experiment was terminated when the producing gas/oil ratio (GOR) reached 3000 m^3/m^3. The displacement pressure, oil production and gas production were measured during the experiment.

In sweeping area regulation experiment, relatively low permeability area was designed to be firstly displaced to enlarge CO_2 sweeping area. The detailed is explained as follows. ① The 3D physical model was placed into 3D coreholder. The formation temperature was set as 60℃, and same production pressure of P-1, P-2, P-3 and P-4 was set as 8 MPa. ② CO_2 was injected through I-1 with the injection rate of 1.5 mL/min. P-4 located in relatively low permeability area was firstly opened, while P-1, P-2, and P-3 located in relatively high permeability area were closed. ③ As the displacement of CO_2 flooding, P-1, P-2, and P-3 were then opened when the producing GOR of P-4 reached 1000 m^3/m^3. ④ The experiment was terminated when the producing GOR reached 3000 m^3/m^3. The displacement pressure, oil production and gas production were measured during the experiment.

In differential pressure control experiment, different production pressure was set by BPRs in different permeability area. The detailed sequence is explained as follows. ① The 3D physical model was placed into 3D coreholder, and the formation temperature was set as 60℃. ② The BPR pressures of P-1, P-2 and P-3 were set as 8.2, 8.3 and 8.2 MPa, and P-4 was set as 8 MPa. ③ CO_2 was injected through I-1 with the injection rate of 1.5 mL/min, and all the producers were opened simultaneously. ④ The experiment was terminated when the producing GOR reached 3000 m^3/m^3. The displacement pressure, oil production and gas production were measured during the experiment.

In real-time producing regulation experiment, the production pressure was real-time regulated by BPRs to achieve similar oil and gas production performance during CO_2 flooding. The detailed sequence is explained as follows. ① The 3D physical model was placed into 3D coreholder, and the formation temperature was set as 60℃. ② The BPR pressures of P-1, P-2 and P-3 were initially set as 8.2, 8.3 and 8.2 MPa, and P-4 was initially set as 8 MPa. ③ CO_2 was injected through I-1 with the injection rate of 1.5 mL/min, and all the producers were opened simultaneously. ④ When CO_2 was breakthrough in the producers, the production pressure was real-time regulated by changing BPRs to achieve similar gas and oil production performance. ⑤ The experiment was terminated when the producing GOR reached 3000 m^3/m^3. The displacement pressure, oil production and gas production were measured during the experiment.

3 Results and discussion

3.1 Oil recovery increment by CO_2 performance control flooding

CO_2 flooding efficiency was seriously affected by the heterogeneity of reservoir. In order to improve the flooding efficiency and enhance oil recovery of CO_2 flooding, performance control methods including sweeping area regulation, differential production pressure control and real-time producing regulation were studied in the experiments to improve the performance of CO_2 flooding in areal heterogeneous reservoir. The experimental results of performance control methods for CO_2 flooding are shown in Table 1. The oil recovery of conventional CO_2 flooding without performance control was 25.85%, while the recovery of CO_2 flooding with performance control methods by sweeping area regulation, differential production pressure control and real-time producing regulation were 42.50%、45.56% and 49.25%, respectively. The oil recovered by performance control methods was almost twice as the oil recovered without performance control during CO_2 flooding.

Table 1 Experimental results of CO_2 performance control flooding

	Producer No.	Permeability ($\times 10^{-3}\mu m^2$)	Performance control methods			
			Conventional CO_2 flooding	Sweeping area regulation	Differential pressure control	Real-time producing regulation
Oil recovery	P-1	50	6.13	5.98	12.46	11.99
	P-2		12.18	10.00	13.52	13.39
	P-3		5.52	7.75	11.22	11.58
	P-4	10	2.02	18.77	9.22	12.29
	Total	/	25.85	42.50	46.42	49.25

Oil recovery of each individual well in production control flooding experiments is shown in Fig.4. In conventional CO_2 flooding without production control treatment, the oil recovery was mostly achieved by the producers of P-1, P-2, and P-3 located in the relatively high permeability area, especially P-2, and the oil recovery of P-4 located in relatively low permeability area was only 2.02% after producing GOR reached 3000m^3/m^3. CO_2 was mostly injected into the relatively high permeability area, especially along P-2 direction, and then left plenty of crude oil remained in both relatively high permeability area and relatively low permeability area.

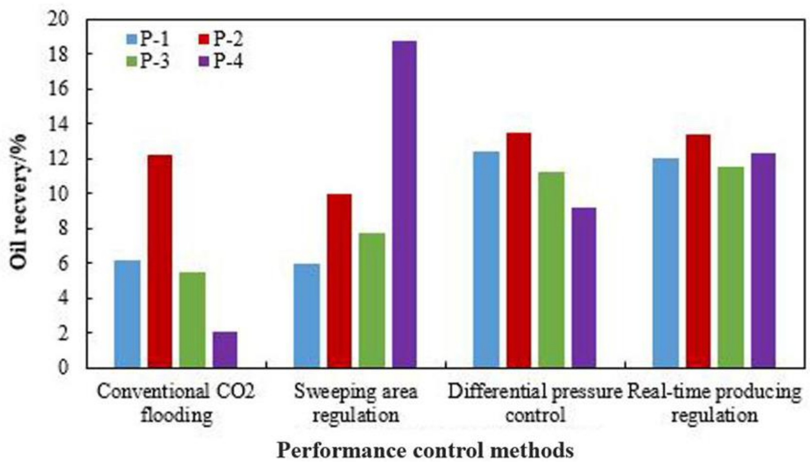


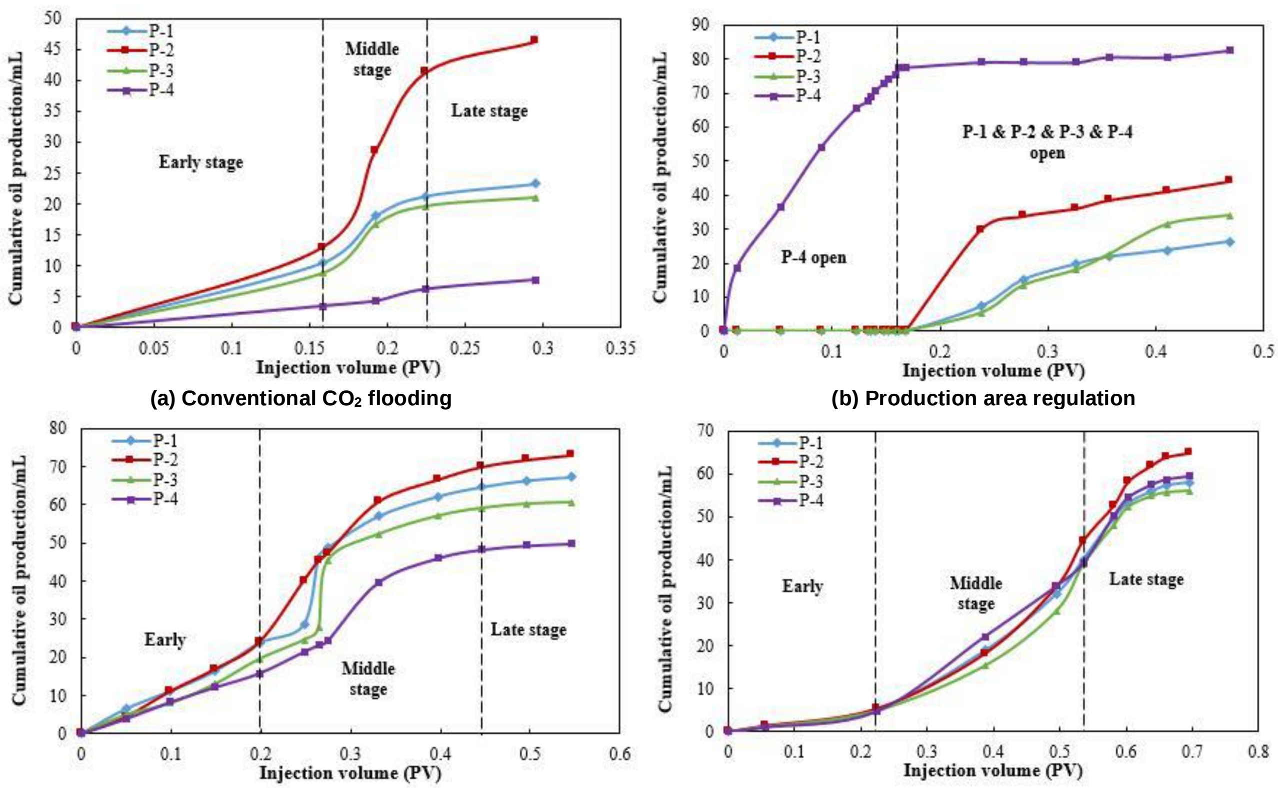
Fig.4 Oil recovery of individual well in CO_2 performance control flooding

In order to effectively displace the oil in relatively low permeability area, sweeping area regulation experiments was designed to firstly displace relatively low permeability area, and then the relatively high permeability area. With the sweeping area regulation, more than 16.65% OOIP was recovered compared of the conventional CO_2 flooding. Through sweeping area regulation, the relatively low permeability area was effectively swept, and the oil recovery of P-4 located in relatively low permeability area contributed significantly to the total recovery of the injection-production unit. Comparatively, differential pressure control and real-time producing regulation achieved higher total oil recovery. The oil produced by each individual well was more balanced, which means that the displacement front of injected CO_2 was more even in the 5-spot injection-production unit. The production control treatments of differential pressure control and real-time producing regulation can not only enlarge CO_2 sweeping area, but also achieve better flooding profile of CO_2 in areal heterogeneous reservoir.

3.2 Performance analysis of CO_2 performance control flooding

The performance of CO_2 flooding in the injection-production unit was further analyzed to discuss the mechanisms of enhancing oil recovery by performance control methods for CO_2 flooding in areal heterogeneous reservoir. Cumulative oil production of each individual well in CO_2 performance control flooding is shown in Fig.5. In conventional CO_2 flooding as shown in Fig.5(a), the oil production of each individual well showed great difference without performance control methods. P-2 located in relatively high permeability area with the best petrophysical condition achieved the highest oil production, while the oil productions of P-1 and P-3 were similar which were both affected by the relatively low permeability area. However, lowest productivity of P-4 lead to the lowest oil production with little CO_2 injected into the relatively low permeability area.

In sweeping area regulation experiment as shown in Fig.5(b), P-4 achieved the highest oil production because CO_2 was firstly injected into relatively low permeability area. However, fluid diversion occurred immediately when P-1, P-2 and P-3 opened. CO_2 was then mostly injected into relatively high permeability area, leading to the very low productivity of P-4 again. Although the relatively low permeability area can be effectively swept by sweeping area regulation, the oil production of individual well still remained uneven in the injection-production unit during CO_2 flooding process.



(a) Conventional CO_2 flooding (b) Production area regulation

(c) Differential pressure control (d) Real-time producing regulation

Fig.5 Cumulative oil production of individual well in CO_2 performance control flooding

Comparatively, similar productivity of individual well can be achieved by production pressure control treatments and real-time producing regulation during CO_2 flooding in areal heterogenous model as shown in Fig.5(c) and Fig.5(d). It is worth notice that CO_2 flooding process can be subdivide into three stages: early stage with no gas producing, middle stage with gas and oil producing simultaneously, and late stage with plenty of gas breakthrough in the producers. In convetional CO_2 flooding, cumulative oil production of individual well increased greatly in the middle stage of the process, and the middle stage can be effectively prolonged by differential pressure control. However, the cumulative oil production increased greatly in the late stage by real-time producing regulation. In other words, although the individual-well productivity of real-time producing regulation was less than the productivity of differential pressure control in the early and middle stage of CO_2 flooding, highest oil recovery could still be achieved with more oil produced from the late stage of real-time producing regulation.

The displacement period of CO_2 flooding can also be significantly prolonged by performance control methods. Table 2 is the gas production performance of each individual well in performance control experiments. The total CO_2 injection volume of conventional CO_2 flooding, sweeping area regulation, production pressure control, and real-time producing regulation was 0.28, 0.47, 0.55 and 0.69 PV, respectively. In conventional CO_2 flooding, CO_2 breakthrough with injectional volume of 0.16 PV, and channeled with injectional volume of 0.28 PV when production GOR reached 3000 m^3/m^3. And no gas was produced through P-4 located in relatively low permeability area. In sweeping area regulation, CO_2 breakthrough firstly in P-4 with injection volume of 0.11 PV, then breakthrough in P-1, P-2 and P-3 with injection volume of 0.21 PV. And when CO_2 channeled in P-1, P-2 and P-3, no gas was produced through P-4 with the gas diversion to relatively high permeability area. In differential pressure control and real-time producing regulation, CO_2 was produced almost the same time both in the relatively high permeability area and the relatively low permeability area, which also reflect the more even displacement by the differential pressure control and real-time producing regulation.

Table 2 Gas production of individual well in CO_2 performance control flooding

	Performance control methods	Relatively higher permeability area			Relatively lower permeability area
		P-1	P-2	P-3	P-4
Time of CO_2 breakthrough /PV	Conventional CO_2 flooding	0.16	0.15	0.16	-
	Sweeping area regulation	0.21	0.20	0.21	0.11
	Differential pressure control	0.19	0.19	0.19	0.20
	Real-time producing regulation	0.22	0.22	0.22	0.22
Time of producing GOR>3000m^3/m^3 /PV	Conventional CO_2 flooding	0.28	0.27	0.28	-
	Sweeping area regulation	0.47	0.46	0.47	-
	Differential pressure control	0.55	0.55	0.55	0.55
	Real-time producing regulation	0.69	0.69	0.69	0.69

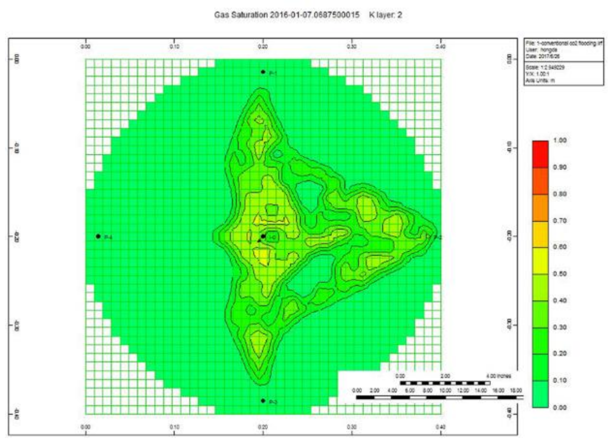
3.3 Corescale numerical simulation of CO_2 performance control flooding

Although the mechanisms of enhancing oil recovery by performance control methods for CO_2 flooding in areal heterogeneous reservoir were analyzed above, CO_2 displacement front cannot be observed directly in the laboratory experiments. In order to further study the profile improvements of CO_2 flooding by the performance control methods, corescale numerical modeling was built using CMG-GEM Simulator. The diameter of the model was 400mm, and the thickness was 45mm, which was the same as the 3D physical model. An injection-production unit of 5-spot pattern was also designed in the numerical model, with P-1, P-2, P-3 located in relatively high permeability area, and P-4 located in relatively low permeability area. The well spacing between injector and producer is 190mm. The oil viscosity is 1.20 mPa·s, and the initial oil saturation is 0.50. Other parameters of the corescale numerical model are summarized in Table 3.

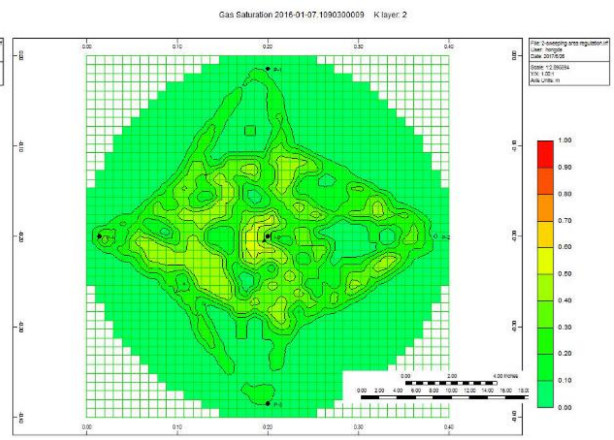
Table 3 Parameters of the corescale numerical model

Parameter	Value	Parameter	Value
Reservoir depth (m)	3189.65	Average porosity	0.18
WOC (m)	3189.675	K of higher permeability area ($\times10^{-3}\mu m^2$)	50
Reservoir temperature (K)	333.15	K of lower permeability area($\times10^{-3}\mu m^2$)	10
Initial formation pressure (psi)	1160.30	Permeability ratio V_k	5

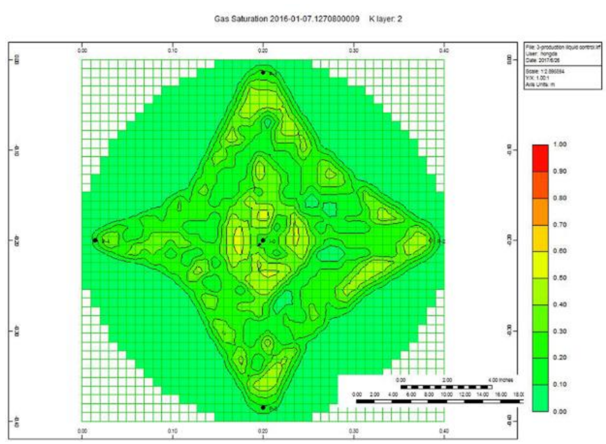
Similar to the 3D laboratory experiments, conventional CO_2 flooding, sweeping area regulation, differential pressure control and real-time producing regulation were also conducted respectively in the corescale numerical models. The gas saturation distributions of CO_2 performance control simulations are shown in Fig.6. Fig.6 visually impressed the flooding profile of CO_2 in the areal heterogeneous model, which was in accordance with the 3D experimental results. In conventional CO_2 flooding without performance control methods, the injected gas mostly displaced along relatively high permeability area, and only part of relatively low permeability area near the injection well (I-0) was swept when the producing GOR reached $3000 m^3/m^3$ (as shown in Fig.6(a)). In sweeping area regulation, both the relatively high permeability area and the relatively low permeability area were swept by CO_2. The relatively low permeability area was firstly swept when P-4 was opened, and the relatively high permeability area was then swept after P-1, P-2 and P-3 opened (as shown in Fig.6(b)). Compared with conventional CO_2 flooding and sweeping area regulation, the relatively high permeability area and relatively low permeability area can be swept simultaneously by differential pressure control and real-time producing regulation. With differential pressure control and real-time producing regulation, the displacement front of CO_2 tended to be more even, and larger sweeping area can be achieved when the producing GOR reached $3000\ m^3/m^3$ (as shown in Fig.6(c) and Fig.6(d)).



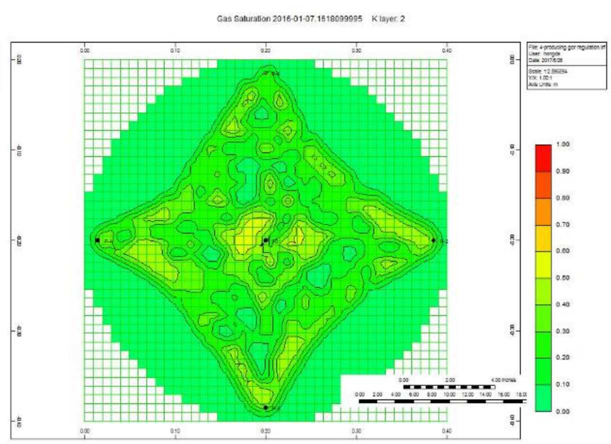
(a) Conventional CO_2 flooding



(b) Sweeping area regulation



(c) Differential pressure control



(d) Real-time producing regulation

Fig.6 Gas saturation distributions of CO_2 performance control simulations

The numerical results of CO_2 performance control flooding were consistent with the 3D laboratory experiments. As a summarize, CO_2 flooding performance of areal heterogeneous reservoir can be improved by simply performance control methods such as sweeping area regulation, differential pressure control or real-time producing regulation, which provided a feasible technical strategy for enhanced oil recovery of the well group in the oil field under the condition of a lower oil price.

4 Conclusion

The oil recovery of areal heterogeneous reservoir could be significantly enhanced by CO_2 perofrmance control flooding. Through the experimental and numerical simulation of performance control methods, some conclusions can be summarized as follows.

(1) CO_2 was displaced unevenly in the areal heterogeneous reservoir, leaving plenty of oil remained in the relatively high and relatively low permeability area. Through performance control methods of sweeping area regulation, differential pressure control or real-time producing regulation, the oil recovery can be doubled during CO_2 flooding process.

(2) The relatively low permeability area can be effectively displaced by prerformance control method of sweeping area regulation, which contributed significantly to the total oil recovery of the injection-production unit.

(3) Through performance control methods of differential pressure control and real-time producing regulation, not only the sweeping area can be effectively enlarged, but also CO_2 profile improvement can be achieved.

(4) Through performance control method of differential pressure control, higher productivity of individual well can be obtained in the early and middle stage of CO_2 flooding. While, similar oil & gas production performance and longer displacement period of CO_2 injection can be achieved by real-time producing regulation.

(5) The performance improvement of CO_2 flooding by performance control methods provided a feasible technical strategy for enhancing oil recovery of areal heterogeneous reservoir in the oil field under the condition of a lower oil price.

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