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CO_2-EOR in Fractured Ultra-Low Permeability Reservoirs: Problems and Remedial Measures

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Abstract

H-3 Block is an ultra-low permeability reservoir in Changqing oil field, China which had been waterflooded from 2009 and was switched to CO_2 flooding in 2013 due to excess water production. However, the nature fractures in NE-SW region have resulted in early CO_2 breakthrough and poor production performance. The investigation of CO_2 production performance and the method to control CO_2 production becomes a key to continue CO_2-EOR project.

Outcrop cores are used to perform a series of CO_2 flooding experiments at reservoir conditions of pressure, temperature and formation water salinity. Permeability heterogeneity and injection pressure are considered as two variables to affect gas channeling characteristics. It is figured out that producing gas-oil ratio and components analysis of effluent could be used to judge gas channeling and timing to control CO_2 production for field use. Starch gel is developed to control CO_2 production within nature fractures to improve CO_2 swept volume in rock matrix. Ethylenediamine (EDA) is proposed to delay CO_2 production within high-permeability zones, and the application boundary as a function of permeability heterogeneity is determined.

Three production stages are clearly stated based on production performance and experimental observation, including gas-free production stage, oil/gas co-production stage, and gas channeling stage. A significant new finding is that oil/gas co-production stage contributes the most to oil recovery. And oil-CO_2 mass transfer zone, rather than free CO_2, reaches the outlet at this stage, which is proved by color of effluent and chromatographic analysis. For field cases, producing gas-oil ratio and components analysis of effluent at wellhead could help field engineers make a decision: keep producing with caution at oil-gas co-production stage or control the CO_2 production at gas channeling stage. The conformance improvement and the increase in injection pressure could remarkably enhance the oil recovery at oil/gas co-production stage. To delay gas channeling and extent oil/gas co-production stage, two-level gas channeling control is presented. A slug of starch gel is first injected to block fractures and then ethylenediamine is injected to react with in-situ CO_2 within high-permeability zone. The starch gel, acting as pure viscous fluid, would not leave contamination in rock matrix. And the viscous reactant of ethylenediamine and in-situ CO_2 could successfully tune injected CO_2 to flood low-permeability zone when permeability ratio is less than 100.

Poor sweep efficiency and immiscibility seriously limit field application of CO_2-EOR, especially in fracture reservoirs. The novelty of this study is to present a new approach for field engineers to judge CO_2 channeling and make the right decision at right time. Two-level gas channeling control is developed to improve CO_2 sweep efficiency and oil production performance in fractured reservoirs.

Keywords: CO_2-EOR, fractured sandstone reservoirs, gas channeling characteristic, CO_2 production control, laboratory experiment

Introduction

There are many difficulties in ultra-low permeability reservoir water flooding development; the micro sweep efficiency is low, and the injection water pressure is high. So, CO_2 flooding has obvious advantages in the development of low permeability reservoir, and has been widely used in many domestic and foreign oil fields. However, because of gravity overriding and viscous fingering, the channeling of CO_2 is very serious. Moreover, with the increase of reservoir heterogeneity, gas can easily penetrate along the high permeable layer, and the effect of CO_2 flooding is obviously reduced. Therefore, gas channeling is a key problem to be solved during CO_2 flooding in ultra-low permeability reservoirs. Right understanding of CO_2 channeling characteristics has important guiding significance for improving CO_2 flooding in low permeability reservoirs.

Many scholars have done a lot of research on CO_2 channeling, but there is no unified understanding. The injection pressure of CO_2 and the heterogeneity of reservoir have a significant influence on gas channeling characteristics.

When the temperature is above 31℃ and the pressure is larger than 7.382MPa, CO_2 will be in a supercritical state. The viscosity is close to the gas, the density is close to the liquid, and it has a strong extraction and dissolution capacity. Further increasing in pressure, CO_2 and crude oil will be miscible. The increase of injection pressure is beneficial to extracting the formation of crude oil, and also to some extent influence CO_2 channeling characteristics. When the reservoir heterogeneity is very serious, CO_2 is advanced along the high permeability layer. Especially, when nature fractures are developed, CO_2 forms the gas channel easily along the fractures, greatly reducing the sweep efficiency. This will lead to a large amount of CO_2 gas in a futile cycle in the formation, influencing the ultimate recovery.

In order to further clarify the gas channeling law of CO_2 flooding in ultra-low permeability reservoirs, this paper analyzes the production characteristics of CO_2 flooding in ultra-low permeability reservoirs under the conditions of reservoir temperature and pressure. And taking CO_2 injection pressure and reservoir heterogeneity into account, their influence on the CO_2 flooding of ultra-low permeability reservoirs is studied. This paper was based on preliminary laboratory research of Hao et al. (2015). Two-stage gas channeling control is proposed and optimized. This study could provide an experimental guide for the prevention and control of CO_2 gas channeling in field case.

Experiments

Materials

- Cores: Natural outcrop cores, artificial cores (the permeability ratios are 5,10,15 and 20) and fractured core with the size of 30*4.5*4.5 cm are utilized in the 1-D flooding experiments; Two layers solid circular artificial cores (the permeability ratios are 10) with the size of Φ45*4.5 cm are utilized in the 3-D flooding experiments. Table 1 shows the basic data for the experimental cores.
- Gas: CO_2 (Purity≥99.00%, Beijing, China)
- Water: Simulating the formation of Huang 3 block in Changqing Oilfield, The salinity of the brine is 61.2 g/L and the water type is $CaCl_2$.
- Oil: The oil sample and are collected from the layer of Huang 3 block in Changqing Oilfield. The crude oil has a viscosity of 2.16 mPa·s and a density of 0.768 g/cm^3 at a temperature of 86.2 ℃
- Modified starch gel system: Modified starch (content, ≥99.00%, Beijing, China), monomer of acrylic amide (content, ≥98.00%, Beijing, China), crosslinking agent (content, ≥98.00%, Beijing, China), initiator (content, ≥99.00%, Beijing, China) and stabilizer (content, ≥98.00%, Beijing, China) were used to form the gel systems with brine.
- Polymer gel system (called PLS gel): Modified starch gel system: polymer (content, ≥99.00%, Qingdao, China), Additive (content, ≥99.00%, Qingdao,

China), crosslinking agent (content, ≥98.00%, Beijing, China), deoxidizer (content, ≥99.00%, Qingdao, China) and stabilizer (content, ≥98.00%, Qingdao, China) were used to form the gel systems with brine.

Table 1 Experimental core data

Types of cores	Core number	Gas permeability ($\times10^{-3}\mu m^2$)	Permeability ratio	Porosity volume (cm^3)	Porosity (%)	Oil saturation (%)
Homogeneous	CQJZ-1	5	1	89	14.65	53.93
	CQJZ-2			90	14.81	51.11
	CQJZ-3			96	15.80	51.00
	CQJZ-4			92	15.14	54.35
	CQJZ-5			92	15.14	45.65
Heterogeneous	CQFJZ-5	5/25	5	98	16.13	48.98
	CQFJZ-10	5/50	10	130	21.40	42.31
	CQFJZ-15	5/75	15	135	22.22	44.44
	CQFJZ-20	25/500	20	128	21.07	35.94
	CQLF	Fracture permeability /5	-	148	24.63	57.63

Experimental equipments

The main experimental equipment used in the experiment include KDHW-II Incubator, Isco pump, Core Holder ($30\times4.5\times4.5cm^3$), Core Holder System (Φ 45*4.5cm), Piston Intermediate Container, Return Valve, D07-11C Gas flow meter, Pressure transmitter. Fig. 1 shows the set-up of this experiment.

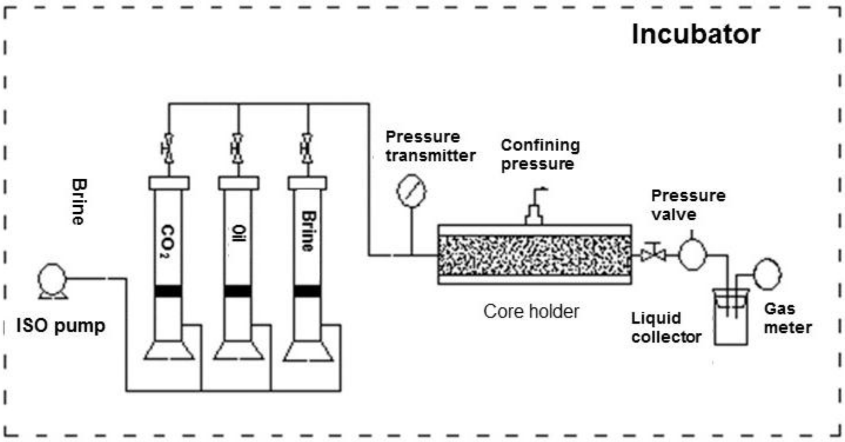


Fig.1 CO_2 flooding experimental set-up

Experimental procedure

The experiment is divided into two major parts, one is to study gas channeling law with homogeneous and heterogeneous cores and the fracture model, the other is to optimize two-stage gas channeling control with fractured two layers solid circular artificial cores, which is used to improve displacement result. The law of gas channeling is studied from two aspects: the heterogeneity and CO_2 phase. By optimizing the two-stage blocking agent to screen out the best combination of blocking agent.

The bulk volumes of the cores are measured before oil displacement experiments. The cores are firstly evacuated and then saturated with the simulated water. The porosities are determined as the ratio of brine saturation volume to the bulk volume. The permeability of the cores is measured by changing water injection rate from 0.1 to 0.3 mL/min. Subsequently, the cores are displaced by simulated oil to reach the residual water saturation condition. Then the initial oil saturation is calculated using the injected oil volume and the pore volume.

In CO_2 phase scenarios, homogeneous are used in the experiments. The detailed sequence during continuous CO_2 flooding experiments is explained as follows. ①The production pressure setted in this scenarios range from 5 to 25 MPa. ②The phase change of CO_2 in the formation is controlled by changes in pressure, phase transition of CO_2 from gas to supercritical state (not including miscibility) to miscibility. ③The experiment is terminated when the producing gas/ oil ratio reaches 3000mL/mL, which is equal to 3000 Sm^3/m^3 when the CO_2 flooding is non-commercial in the oilfield.

In heterogeneity scenarios, homogeneous and heterogeneous cores and fractured are used in the experiments. The detailed sequence during continuous CO_2 flooding experiments is explained as follows. ①the permeability of the cores used in this scenarios range from 1(homogeneous core) to 20, and one fractured core is also used ②The production pressure is set to be 15 MPa, and the injection rate is 1 mL/min under formation pressure. ③The experiment is terminated when the producing gas/ oil ratio reaches 3000mL/mL, which is equal to 3000 Sm^3/m^3 when the CO_2 flooding is non-commercial in the oilfield.

In two-stage gas channeling control scenarios, fractured two layers solid circular artificial cores are used in the experiments. The detailed sequence during continuous CO_2 flooding experiments is explained as follows. ①The production pressure is set to be 15 MPa, and the injection rate is 1 mL/min under formation pressure. ②The starch gel or PLS gel is injected into the model when the producing gas/ oil ratio reaches 500mL/mL, Then closed for 24 hours waiting to form a gel. ③The EDA or foam is injected into the model when the producing gas/ oil ratio reaches 500mL/mL again.④The experiment is terminated when the producing gas/ oil ratio reaches 3000mL/mL, which is equal to 3000 Sm^3/m^3 when the CO_2 flooding is non-commercial in the oilfield.

Results and Discussion

Fig. 2 depicts production dynamic curve of CO_2 flooding at 15MPa injection pressure. Three production stages are clearly stated based on production performance and experimental observation, including gas-free production stage, oil/gas co-production stage, and gas channeling stage. ①In gas-free production stage, single-phase oil is produced in the form of slugs. ②When the gas appears in the output side, CO_2

flooding enters into the oil/gas co-production stage, in which the oil is a continuous phase while the gas is a dispersed phase. ③When a large number of gas comes out of the core, CO_2 flooding enters into the gas channeling stage, in which the gas phase is continuous coming with a small amount of oil.

Carrying out CO_2 flooding experiment at different injection pressure or under heterogeneous conditions, the displacement characteristics are the same as that shown in the Fig. 2. Whether the gas injection pressure or heterogeneous conditions change, dynamic characteristic curve of CO_2 flooding will be influenced.

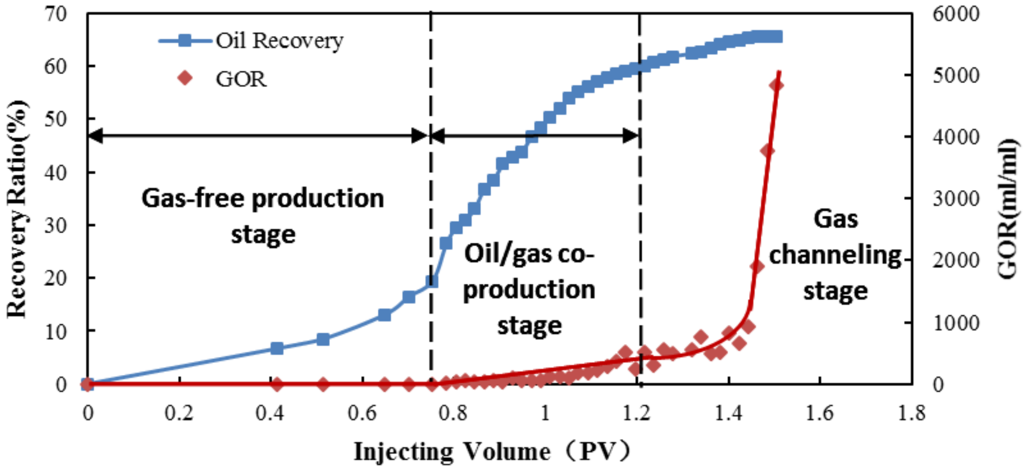


Fig.2 Producing gas oil ratio and recovery curve of supercritical CO_2 immiscible flooding in homogeneous core sample

Effect of CO_2 phase behavior

Table 2 is the experimental results of continuous CO_2 flooding at different injection pressure in homogeneous cores, while Fig.3 depict the oil recovery of each stage with the injection pressure curve during continuous CO_2 flooding. In general, the total oil recovery of CO_2 flooding increases with the increase of injection pressure, but the degree of oil recovery in each stage is different. With the increase of injection pressure, the oil recovery of gas free production stage does not increase very much, which is mainly caused by the basic properties of the core. For ultra-low permeability reservoirs with similar properties, oil and the area of pure oil are similar in gas phase percolation curve, while the increase of the injection pressure slows the gas viscous fingering to a certain extent, which makes the displacement front move more uniform. Relatively, the change of CO_2 injection pressure will change oil and gas two-phase flow region to a large extent, and oil/gas co-production stage and gas channeling stage increased significantly at the macro level. When CO_2 is converted from a gas phase to a supercritical state, the ability of dissolve and diffuse is greatly enhanced, and the ability to extract and extract light hydrocarbons is also significantly improved, so the oil recovery of oil/gas co-production stage is increased significantly. When the injection pressure reaches above 20MPa, CO_2 and oil will form miscible phase, which can greatly enhance the oil recovery, and a certain amount of crude oil can be produced in the gas channeling stage at this condition.

Table 2 Experimental results of CO_2 phase effect on the gas channeling

Core number	Injection Pressure（MPa）	Recovery degree（%）			Total recovery（%）	Injection volume（PV）			Total injection volume（PV）
		gas-free production stage	oil/gas co-production stage	gas channeling stage		gas-free production stage	oil/gas co-production stage	gas channeling stage	
CQJZ-1	5	18.13	9.58	1.14	28.85	0.75	0.24	0.11	1.10
CQJZ-2	10	18.93	25.18	2.26	53.89	0.75	0.35	0.15	1.25
CQJZ-3	15	19.41	40.63	5.57	65.61	0.75	0.47	0.29	1.51
CQJZ-4	20	25.4	48.8	10.4	84.60	0.76	1.0	0.75	2.51
CQJZ-5	25	26.47	51.2	11.25	88.81	0.77	1.1	0.82	2.69

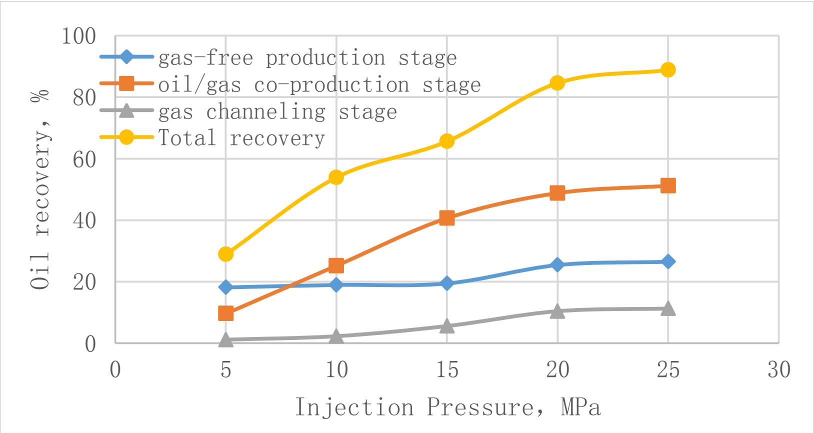


Fig.3 The recovery of each stage with the injection pressure curve

Effect of reservoir heterogeneity

Table 3 is the experimental results of continuous CO_2 flooding at different permeability ratio in heterogeneous and homogeneous cores and fractured model, while Fig.4 depict the oil recovery of each stage with the heterogeneity during continuous CO_2 flooding. On one hand, with the increase of core heterogeneity, the total recovery rate was significantly lower in CO_2 flooding. The recovery of the homogeneous core was significantly higher than that of heterogeneous core and fractured cores, and with the enhance of reservoir heterogeneity, the total injection volume of CO_2 and the injection volume displacement in each stage decrease significantly. the recovery degree of gas-free production stage decreases with the increase of reservoir heterogeneity, but slightly lower. The recovery of gas-free production stage is mainly affected by the reservoir physical properties, flow area of pure oil of low permeability heterogeneous reservoir are similar, so there is the oil recovery of gas-free production stage of small decline. For the fractured reservoir, the oil recovery of gas-free production stage mainly originates from the oil in the cracks. On the other hand, Heterogeneity of the core has a great influence on oil/gas co-production stage and gas channeling stage. Compared with the homogeneous core, when the permeability ratio is 5, the recovery degree of oil/gas co-production stage of the heterogeneous core is obviously decreased. CO_2 is infiltrated along the hypertonic layer, and the injected gas cannot effectively spread to the low permeability reservoir. With the further increase of the permeability difference, the contradiction between the layers increases, and the phenomenon of CO_2 channeling becoming higher and higher. In summary, reservoir heterogeneity mainly affects the development of CO_2 flooding oil/gas co-production stage and gas channeling stage in ultra-low permeability reservoirs. How to improve reservoir heterogeneity effectively, and to prevent the injection of gas along the hypertonic layer or crack, which is the key point to improve the development of CO_2 flooding in ultra-low permeability reservoirs.

Table 3 Experimental results of heterogeneity effect on the gas channeling

Core NO.	Permeability ratio	Recovery degree（%）			Total recovery（%）	Injection volume（PV）			Total injection volume（PV）
		gas-free production stage	oil/gas co-production stage	gas channeling stage		gas-free production stage	oil/gas co-production stage	gas channeling stage	
CQJZ-3	1	19.41	40.63	5.57	65.61	0.75	0.47	0.29	1.51
CQFJZ-5	5	17.95	24.25	5.39	47.59	0.54	0.49	0.39	1.42
CQFJZ-10	10	17.56	21.39	4.31	43.26	0.45	0.39	0.34	1.18
CQFJZ-15	15	17.25	20.16	3.97	41.38	0.41	0.36	0.28	1.05
CQFJZ-20	20	16.96	19.45	3.81	40.22	0.39	0.27	0.24	0.9
CQLF	fracture	14.31	15.74	1.32	31.37	0.25	0.2	0.15	0.6

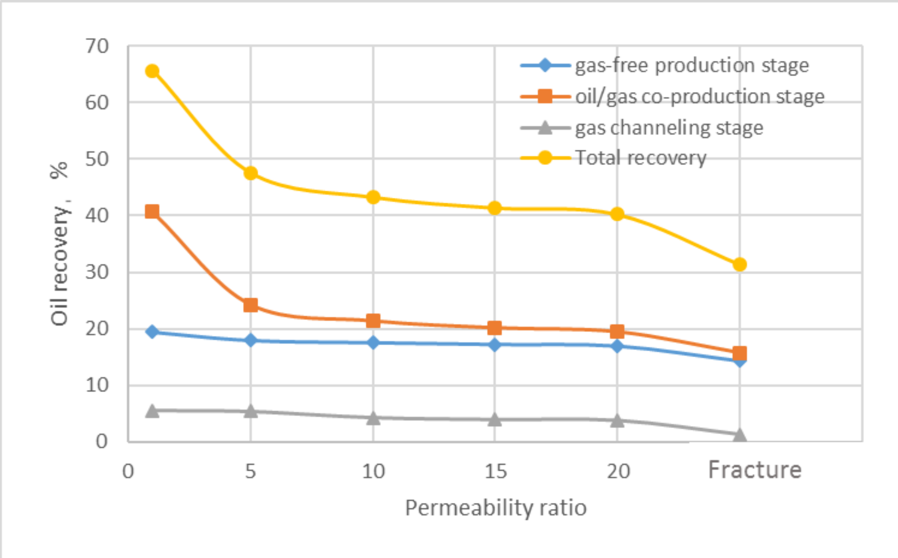


Fig.4 The recovery of each stage with the Permeability ratio curve

Two-stage gas channeling control scenarios

Based on the previous study of the law of gas channeling, the method of CO_2 immiscible flooding was carried out in five-spot pattern model, and the plugging process and the process parameters were optimized and evaluated. Fig. 5 is the five-spot pattern model. Three kinds of sealing agent combinations were evaluated including starch gel + EDA combination, PLS gel + EDA combination and starch gel + foam t combination.

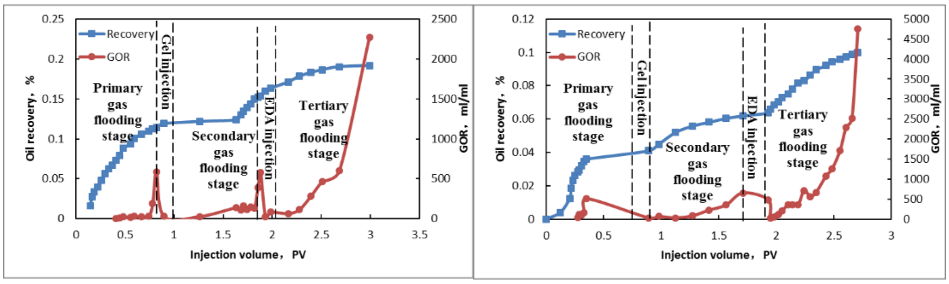
Fig.5 Five-spot pattern model

Starch gel + EDA scenario

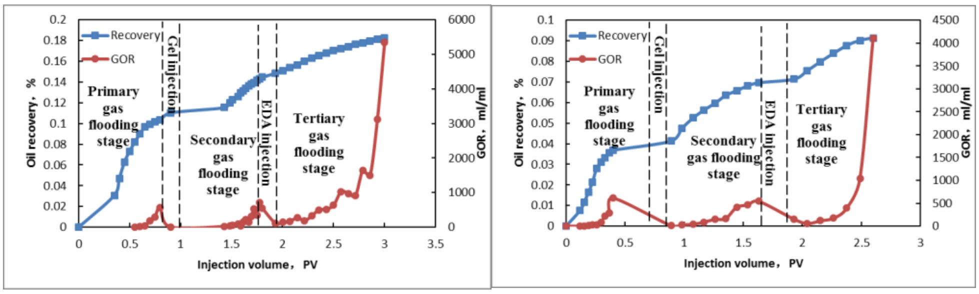
Fig. 6 depict the oil recovery and GOR of each production well during continuous CO_2 flooding. According to the change of production gas and oil ratio in the process of displacement and the different blocking measures, the flooding process can be divided into three stages: primary gas flooding stage, secondary gas flooding stage and tertiary gas flooding stage. Primary gas flooding stage: from the start of the gas injection to the beginning of the gel injection; Secondary gas flooding stage: from the gel injection into the beginning of EDA injection; Tertiary gas flooding stage: from the EDA injection to the end of the experiment.

The production performance curves of four wells are similar. The characteristic of primary gas flooding stage is described as follows: the GOR of gas free period is 0, during which the oil recovery is proportional to the CO_2 injection volume, while the

GOR increases rapidly as gas breakthrough, and the recovery curve tends to be flat, which means CO_2 flows along the fracture. The characteristic of secondary gas flooding stage is described as follows: the production of gasoline is maintained at a relatively low level for a period of time, indicating that the injected gel effectively blocks the cracks, forcing the injected CO_2 to turn toward the core matrix, and the recovery curve does not rise immediately after the injection of the gel, because the effective sealing of the gel has a certain delay. After a while the GOR rises rapidly, which is due to the gas flowing along the high permeability layer caused by matrix heterogeneity, the stage of the recovery curve changes from flat to upturned, and then tends to be flat again. The characteristic of tertiary gas flooding stage is described as follows: the recovery curve is first increased, indicating that the injected EDA is well improved in the heterogeneity of the core, and the production gas curve also declines at the same time. Then the recovery curve is flattened again, and the GOR is increased rapidly.



(a） well 1 （b）well 2



（c） well 3 （d） well 4

Fig.6 The production dynamic curve of each well

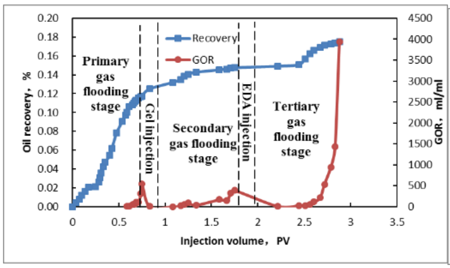
Table 4 is the experimental results of continuous CO_2 flooding with starch gel + EDA in five-spot pattern model. Well 1 and well 3 are far crack wells, and oil recovery of them are 11.44% and 10.35% respectively during primary gas flooding stage. Well 2 and well 4 are near crack wells, which are affected by cracks. The oil recovery of them are 3.596% and 3.692% respectively during the same period. After primary gas flooding stage the cracks are blocked by the starch gel. The results show that the recovery of the four wells is maintained at the same level in the secondary gas flooding stage, the recovery of each well is about 3%, and the total recovery degree is 14.50% in this stage. Similarly, the subsequent injection of EDA improves the heterogeneity of the model to a certain extent, and constantly adjusts the injection profile of CO_2 to inhibit the viscosity of CO_2 in the model, the recovery of the tertiary gas flooding stages is 13.35%. Plugging system of starch gel + EDA enhances oil recovery which reaches 27.85%, and has a good adaptability to reservoir of fracture and serious heterogeneity.

Table 4　Experimental results of starch gel + EDA scenario

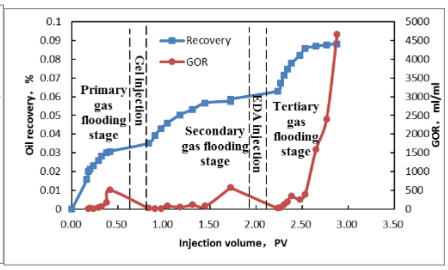
recovery/%	primary gas flooding stage	secondary gas flooding stage	tertiary gas flooding stage	Total recovery
well 1	11.44	3.94	3.79	19.17
well 2	3.596	2.769	3.616	9.981
well 3	10.35	4.52	3.77	18.64
well 4	3.692	3.27	2.17	9.132
Total recovery	29.078	14.499	13.346	56.923

PLS gel + EDA scenario

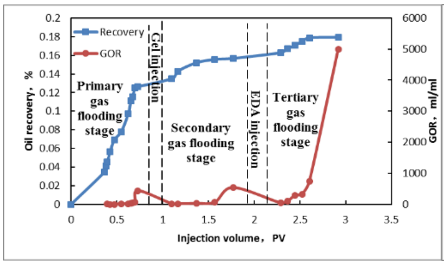
Fig. 6 depict the oil recovery and GOR of each production well during continuous CO_2 flooding. Table 5 is the experimental results of continuous CO_2 flooding with PLS gel + EDA in five-spot pattern model. Similarly, according to the change of production gas and oil ratio in the process of displacement and the different blocking measures, the flooding process can be divided into three stages.



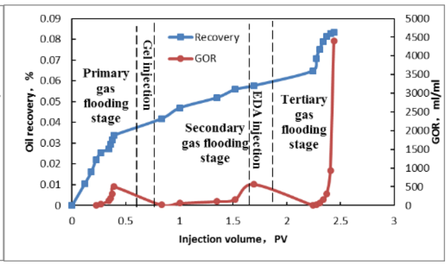
(a) well 1



(b) well 2



(c) well 3



(d) well 4

Fig.7 The production dynamic curve of each well

Table 5 Experimental results of PLS gel + EDA scenario

recovery/%	primary gas flooding stage	secondary gas flooding stage	tertiary gas flooding stage	Total recovery
well 1	11.73	2.846	2.72	17.296
well 2	3.078	2.782	2.957	8.817
well 3	12.63	3.04	2.26	17.93

well 4	3.374	2.377	2.574	8.325
Total recovery	30.812	11.045	10.511	52.368

Table 6 Comparision of Starch + EDA with PLS +EDA

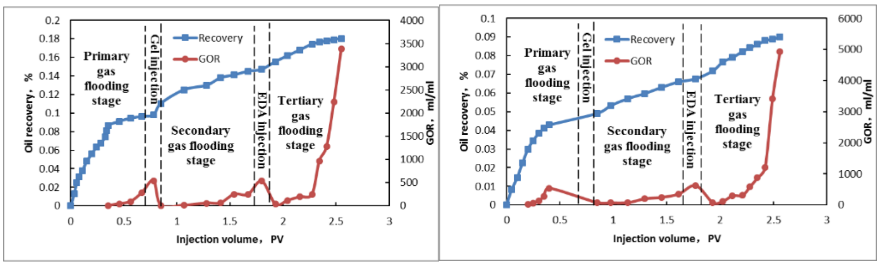
recovery/%	primary gas flooding stage	secondary gas flooding stage	tertiary gas flooding stage	Total recovery
Starch gel+ EDA	29.078	14.499	13.346	56.923
PLS +EDA	30.812	11.045	10.511	52.368

The trend of these four wells is roughly the same as above. The development of near-crack wells is far less than that of far-flung wells, but the production of four can be roughly maintained at the same level after the production measures are taken. Table 5 is comparison of oil recovery of starch gel + EDA system and PLS gel + EDA system at each stage. The recovery of tertiary gas flooding stage reaches 10.51%, which proves PLS + EDA to be adaptable to reservoir of fracture and serious heterogeneity too. However, compared with the starch gel, the recovery of secondary gas flooding stage of PLS gel + EDA is about 3.45% lower than that of starch gel +EDA. And the recovery of tertiary gas flooding stage of PLS gel + EDA is about 2.84% lower than that of starch gel +EDA. Although both cases are injected with EDA at tertiary gas flooding stage, the effect of former is better due to the strong ability of the starch gel to seal the crack. In summary, starch gel in is slightly better than PLS gel the sealing effect, and the sealing effect of the cracks will also directly affect the effect of EDA.

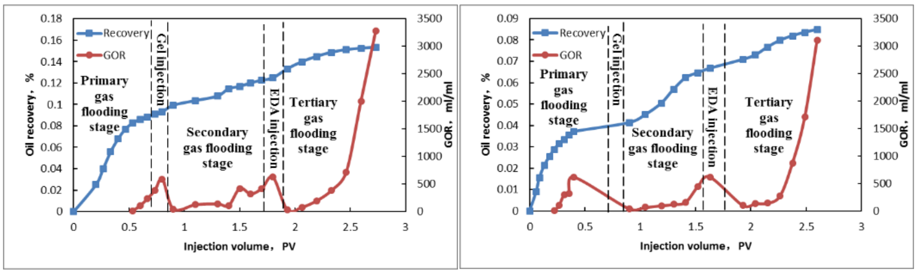
The reasons that starch gels are more resistant to cracks than PLS gels are described as follows. The viscosity modulus of the starch gel is 24.19Pa, and the elastic modulus is 1.335Pa, which is he rigid gel according to the standard, while the viscosity modulus of the PLS gel is 5.802Pa, and the elastic modulus is 0.494Pa, which is the medium strength gel according to the standard. So the starch gel is stronger than the PLS gel. The viscosity of Starch gel is lower than PLS gel at room temperature, the ability of starch gel injection is higher, which makes it more conducive to migration to the deep cracks. In summary, one stage of blocking agent recommended the use of starch gel.

Starch gel + foam scenario

Fig. 8 depicts the oil recovery and GOR of each production well during continuous CO_2 flooding. Table 7 is the experimental results of continuous CO_2 flooding with starch gel + foam in five-spot pattern model. By comparing the recovery of the difference stages of the starch gel + EDA and starch gel + foam system, it is shown that the difference in the degree of primary gas flooding in the two cases is due to the subtle differences in the experimental core. Because of the same two-stage flooding agent, the recovery of tertiary gas flooding stage is not much difference, and the recovery of the former is 3.12% higher than that of the latter, indicating that the foam is not as efficient as EDA in improving heterogeneous cores.



(a) well 1　　　　(b) well 2



(c) well 3　　　　(d) well 4

Fig.8 The production dynamic curve of each well

Table 7　Experimental results of Starch gel + foam combination

recovery/%	primary gas flooding stage	secondary gas flooding stage	tertiary gas flooding stage	Total recovery
well 1	9.79	4.92	3.31	18.02
well 2	4.29	2.48	2.23	9.00
well 3	9.29	3.17	2.88	15.33
well 4	3.71	3.17	1.81	8.69
Total recovery	27.08	13.73	10.23	51.04

EDA is stronger than foam in improving heterogeneous for the following reasons. First, the EDA is very low in viscosity and has good injective ability. It can migrate to the high permeability layer in the matrix, during which it reacts with CO_2 to form a yellow viscous substance, which can effectively block the high permeability layer, while the foam only can increase the power of the displacement process, forcing the gas into the low permeability layer, thus expanding swept volume. but this does not directly plug the effect of high permeability layer. Second, the reaction of EDA with CO_2 can deplete CO_2 in the formation of gas channel, greatly reducing the GOR, which is conducive to shielding the channeling channel, while the foam cannot be a permanent collection of carbon dioxide, once the foam burst CO_2 will be released out. Finally, Alkaline EDA, before being reacted with CO_2, can be used as an alkali to carry out the oil displacement, with excellent performance of alkali flooding, and after the reaction with carbon dioxide can be used as a profile control agent, with dual effects, which are the bubble cannot do.

Conclusions

Heterogeneity and CO_2 phase behavior can greatly affect CO_2 flooding efficiency. The stages of the displacement process can help us to study the law of gas channeling more specifically. Two-level gas channeling control is an effective way to improve CO_2 sweep efficiency and oil production performance in fractured reservoirs. Some conclusions can be summarized as follows.

(1) Three production stages are clearly stated based on production performance and experimental observation, including gas-free production stage, oil/gas co-production stage, and gas channeling stage. A significant new finding is that oil/gas co-production stage contributes the most to oil recovery.

(2) With the increase of CO_2 injection pressure, the recovery degree of the gas free production stage, the oil/gas co-production stage and the gas channeling stage is gradually increased, and the effect of the injection pressure on oil recovery of the oil/gas co-production stage is especially significant. When the injected gas and the oil reaches near-miscible or miscible state, a certain amount of crude oil can still be produced during the gas channeling stage.

(3) With the increase of reservoir heterogeneity, the recovery degree of the gas free production stage, the oil/gas co-production stage and the gas channeling stage is gradually reduced, and the oil recovery of the oil/gas co-production is deeply affected by reservoir heterogeneity. With the increase of reservoir heterogeneity, CO_2 breakthroughs along the hypertonic layer or fractures, and the channeling phenomenon is increasingly significant.

(4) Through the optimization of the two-level gas channeling control system, it is recommended the use of high-strength starch gel as first blocking agent and EDA as secondary blocking agent. The combination of the two chemicals can be a good control of gas channeling, which can greatly enhance oil recovery.

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