Effect of Water-alternating-gas Injection on Gas and Water Production Control in Carbonate Reservoirs

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Abstract

The viscous fingering during continuous gas flooding and water channeling during water flooding will reduce the sweep efficiency and ultimately affect the displacement efficiency. In this paper, extensive experiments with different injection modes were conducted to study their effect on production performance.

Experimentally, based on the geological characteristics and development conditions of the target carbonate reservoir, a laboratory physical model was established to study the migration characteristics and occurrence state of the injected gas and water. The effect of different injection modes, including continuous gas flooding, water-alternating-gas (WAG) flooding and water flooding, on water and gas production and oil-displacement efficiency was investigated. Experimental results indicated that the rising of water cut of WAG flooding was much lower than that of water flooding, presenting a good effect on delaying water production. WAG injection showed a relatively plateau period of gas-oil ratio, indicating injected water delayed gas channeling. WAG flooding achieved the highest oil recovery, followed by continuous gas flooding and water flooding.

This study provided an improved understanding of gas and water channeling behavior, and proposed schemes for delaying gas channeling and improving gas flooding.

Key words: gas flooding; water flooding; gas and water production; water-alternating-gas injection; physical simulation.

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1. Introduction

The target reservoir is a heterogeneous reservoir, and water injection or gas injection is generally used for oil production. There are a lack of natural energy, slow effect, high water cut in the middle and late stages, oil production declining and other issues for conventional water injection [1-3]. Gas (CO_2) flooding is one of the main technologies for enhancing oil recovery. Its unique mechanism of enhanced oil recovery includes viscosity reduction by dissolution, light fraction extraction and interfacial tension reduction. Besides of improving oil recovery, it can also play a role in reducing greenhouse gases and achieve a win-win situation for oil displacement and storage. But gas injection has problems such as premature gas timing and serious gas channeling [4]. Water-alternating-gas (WAG) flooding, as a gas injection method alternately with gas flooding and water flooding, combines the advantages of gas flooding to extract light components, reduce oil viscosity and interfacial tension, and improve the microscopic sweep efficiency of water flooding [5]. It can compensate for the problem of insufficient supply and gas channeling to effectively improve oil recovery.

Based on extensively researches and applications of gas flooding technology, and combined with the target reservoir geology and development conditions, we established an indoor experimental physical model and studied the oil recovery of WAG technology, as well as the behavior of water cut and gas-oil ratio. Comparing the prodcution performance of three different injection methods, the influence of different injection methods on oil recovery was revealed [6-7].

2. Experiments

2.1 Materials and experimental set-up

The materials used in the experiment, including oil, water, gas and core samples, and the experimental stet-up were the same as that in the paper “Experimental Modeling of Gas Channeling for Water-alternating-gas flooding in High-temperature and High-pressure Reservoirs (CMTC-558864)”.

2.2 Experimental procedures and schemes

2.2.1 Water-alternating-gas (WAG) flooding

An artificial carbonate core whose dimensions, permeability ratio, injected rate and back-pressure are given in Tab.1 was wrapped with a mixture of epoxy resin and curing agent.

Tab.1 Basic parameters of alternating injection of water and carbon dioxide

Core permeability (mD)	Back pressure (MPa)	gas-water volume ratio	Gas injection rate (ml/min)	Water injection speed (ml/min)
50/250	25	1：1	0.2	0.2

For coreflooding experiments, the sequence of experiments was as follows.

①Artificial carbonate cores coated with epoxy resin and curing agent were put into the core holder and then confining pressure was added. ②The core was vacuumed for 4-6 hours and saturated with formation water to calculate the permeability of water phase. ③Calculate oil saturation after the core was saturated with crude oil. ④The aging stage of the oil, which lasted 24 hours, was designed to be consistent with the form of crude oil that has been stored in the actual formation for countless years. ⑤According to experimental requirements, different permeability ratio and injection rates were set. ⑥In the way of first gas injection and then water injection cycle alternating injection, the gas-water volume ratio was 1:1. ⑦The experiment was terminated when the producing gas-oil ratio reached 3000 mL/mL.

2.2.2 Water flooding and continuous gas flooding

Water flooding and continuous gas flooding experiments were conducted to compare with the result of WAG flooding. The temperature was set to 84 ℃, and the back pressure was set to 25MPa. The injection rate was 0.2 ml/min. The experiment was stopped until the water cut was greater than 98% or the gas-oil ratio was greater than 3000 mL/mL.

3. Results and discussion

3.1 Analysis of WAG displacement law

As shown in Fig. 1, the entire WAG process can be divided into four production stages. 0-0.1 PV is the first stage, mainly the process of supplying energy and gas dissolution accompanied by viscosity reduction, the oil recovery at this stage is 0.42%. 0.1-0.26 PV is the oil recovery stage without water, the oil produced in this process does not contain water, the oil recovery is 21.77%. The third stage (0.26-0.6 PV) is the stage of simultaneous production of oil, gas and water, also the stage with the highest oil recovery rate in the entire WAG process. Since the flow capacity of the gas is stronger than that of the water, the gas is produced preferentially over the water, and maintain fluctuations in a lower gas production range. When the injection volume reaches 0.307 PV, water production begins, and the water cut increases in a wave-like zigzag. At this stage, the interaction between gas and water effectively prolongs the time of water and gas channeling, and is the most productive and important oil recovery stage in the WAG process. The fourth stage is the gas channeling stage, the ability of gas and water to interact disappears. Gas-oil ratio and water cut rise sharply, no longer fluctuating. The oil recovery rate is weak and basically stabilizes.

The first stage: Mainly to supplement the formation energy and gas dissolution and viscosity reduction stage (t=0.1 PV, Ro=0.42%);

second stage: Waterless production stage (t=0.1-0.26 PV, Ro=21.77%);

The third stage: At the stage of simultaneous production of oil, gas and water, the water content increases in a wave-like tortuosity (t=0.26-0.6 PV, Ro=48.44%);

Fourth stage: Gas channeling（t=0.6-0.75 PV，Ro=1.25%）.

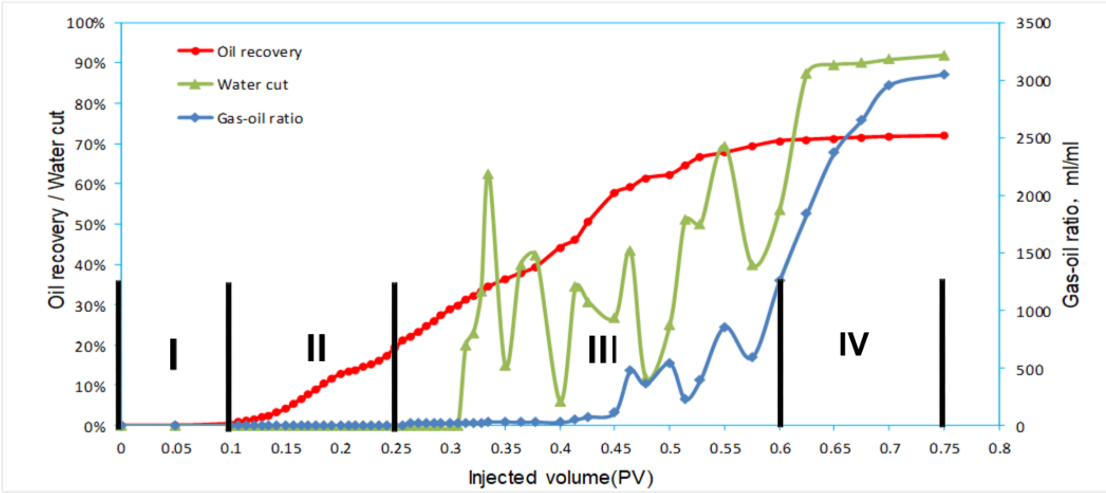

Fig. 1 Producing gas-oil ratio, water cut and oil recovery of continuous gas flooding in heterogeneous core sample (Q=0.2ml/min, vk=5)

3.2 Comparison of water cut changes

As shown in Figs. 2 and 3, WAG see water time (t=0.307 PV) is much later than continuous water flooding (t=0.093 PV), and the rate of water cut rises much less than continuous water flooding, the law of water rise rises from S type to concave type. It shows that the injection of gas plays an effective role in water control, which makes the oil recovery of WAG far higher than that of continuous water flooding.

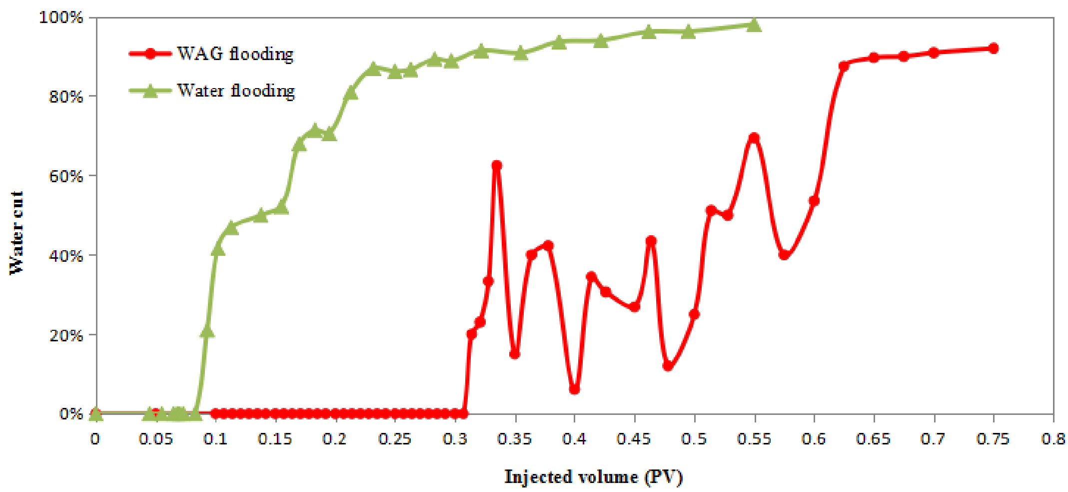

Fig. 2 Comparison of water cut of water flooding and WAG flooding

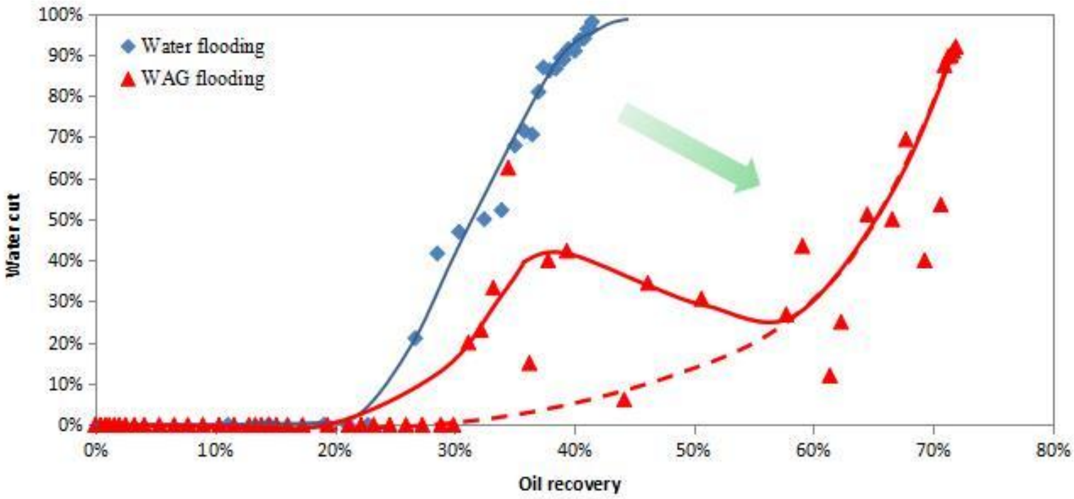

Fig. 3 Relationship of water cut and oil recovery for water flooding and WAG flooding

3.3 Comparison of gas-oil ratio

As can be seen from Fig. 4, the rising phase of the gas-oil ratio during the WAG process (Ro=60%) lags significantly behind the continuous gas flooding (Ro=40%). A large amount of crude oil was produced under low gas-to-oil ratio conditions, indicating that the injection of water played a role in delaying the gas. However, in the later stage, the formation of gas channeling and the loss of water to inhibit the ability of gas led to a sharp rise in gas-oil ratio. The increase in oil recovery rate tends to be flat, which also indicates that although the injection of water can delay the gas channeling, it cannot completely prevent the gas channeling.

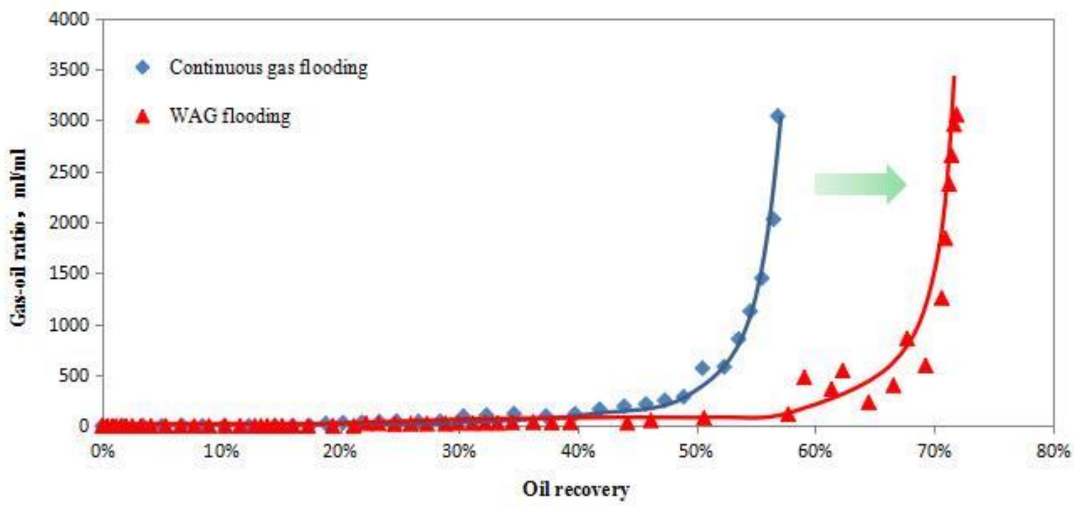

Fig. 4 Relationship of gas-oil ratio and oil recovery for continuous gas flooding and WAG flooding

3.4 Comparison of oil recovery

Comparing Figs. 1, 5, and 6, at the same pressure, temperature and injection rate, the gas flooding recovery is better than water flooding for cores with a permeability difference of 5, which can be increased by about 14 percentage points. The oil recovery rate of WAG is significantly better than gas flooding, which can increase by about 15 percentage points. In the process of WAG, the water cut first rises and then falls, showing a tendency of reciprocating fluctuations. After seeing the water, in the range of fluctuations in water cut, the rate of oil recovery increases rapidly, which is a high-yield period.

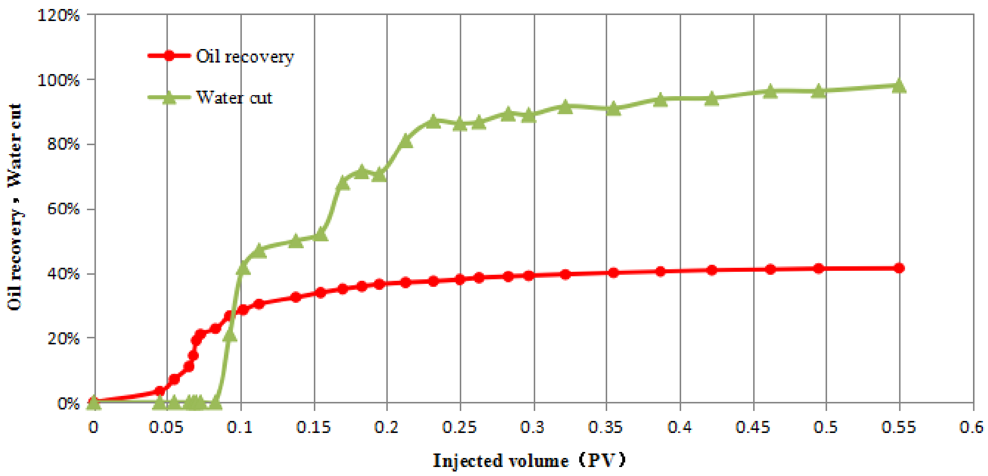

Fig. 5 Water cut and oil recovery of water flooding

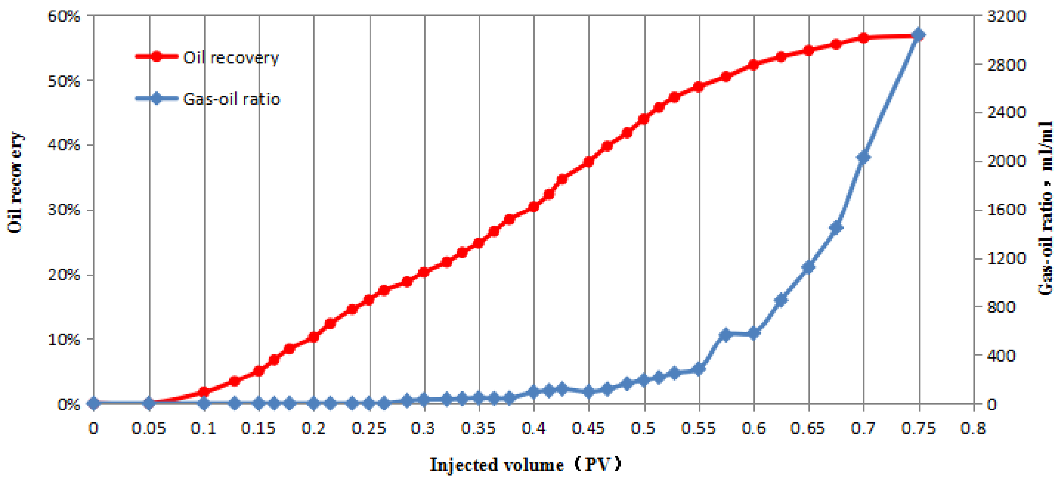

Fig. 6 Producing gas-oil ratio and oil recovery of continuous gas flooding

Comparing the production performance of three different injection methods (as shown in Fig. 7), the injected water has low compressibility and strong energy supplement effect, the effect of improving oil recovery in the early stage is obvious, and the displacement in the middle and late stages is obviously insufficient. In the mid-term of gas flooding, the effect of enhanced oil recovery is more obvious, but gas channeling will greatly reduce the oil recovery. The technology of WAG combines the advantages of both water flooding and gas flooding, and the oil recovery rate is the most obvious, with the highest degree of recovery.

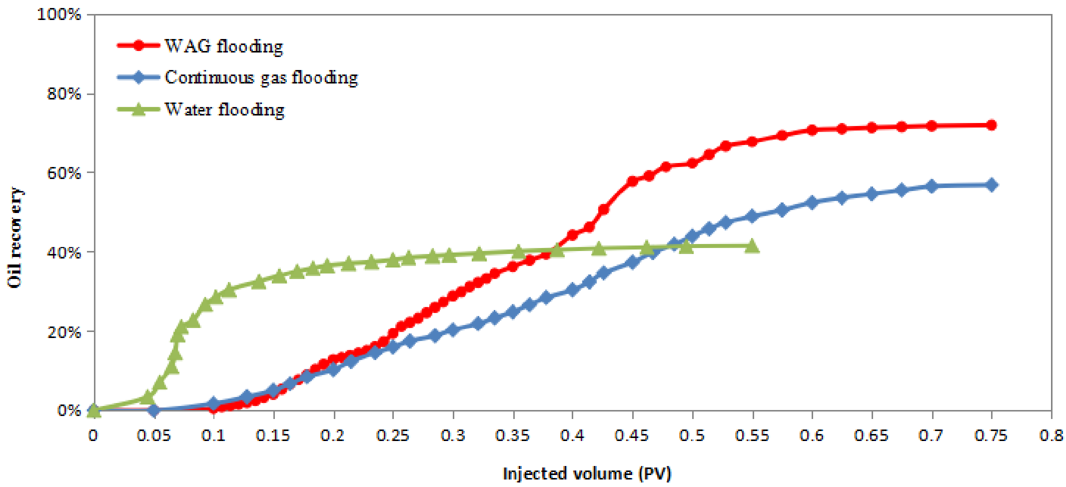

Fig. 7 Oil recovery of water flooding, continuous gas flooding and WAG flooding

4. Conclusions

(1) WAG flooding achieved a significantly higher oil recovery than continuous gas flooding and water flooding. Compared with continuous gas flooding, the oil recovery rate can be increased by about 15%. Compared with water flooding, the oil recovery rate can be increased by about 30%. WAG combined both the advantages of water flooding and gas flooding.

(2) Water-alternating-gas injection presented a good effect on water control. In the process of WAG, the water cut first rose and then fell, showing a tendency of

reciprocating fluctuations. After water breakthrough, in the period of water cut fluctuation, the oil recovery increment was highest and the duration was the longest.

(3) Gas-oil ratio increased sharply after 0.6 PV was injected for both continuous gas flooding and WAG flooding.

References

[1] YUAN Shiyi, WANG Qiang. New progress and prospect of oilfields development technologies in China [J]. Petroleum Exploration and Development, 2018, 45 (4) : 657-668.

[2] HU Wenrui, WEI Yi, BAO Jingwei. Development of the theory and technology for low permeability reservoirs in China [J]. Petroleum Exploration and Development, 2018, 45 (4) : 646-656.

[3] Li Shilun, ZHOU Shouxin, DU Jianfen, et al. Review and prospects for the development of EOR by gas injection at home and abroad [J]. Petroleum Geology and Recovery Efficiency, 2002, 24 (2) : 1-5.

[4] Li Zhenquan, YIN Yong, WANG Qiwei, et al. Development of the research on EOR mechanism by WAG [J]. Journal of Southwest Petroleum University (Science ＆Technology Edition) , 2007, 29 (2) : 22-26.

[5] ZHOU Xingze, LIAO Xinwei, ZHAO Xiaoliang, et al. Laboratory investigation of miscible CO_2 WAG process in extra-low permeability reservoir [J]. Journal of Shanxi University of Science ＆ Technology (Natural Science Edition) , 2016, 34 (6) : 120-124.

[6] CHEN S, LI H, YANG D, et al. Optimal parametric design for water alternating-gas（WAG）process in a CO_2-miscible flooding reservoir [J]. Journal of Canadian Petroleum Technology, 2010, 49 (10): 75-82.

[7] NEZHAD SART, MOJARAD MR, OSKOUEI S J P, et al. Experimental study on applicability of water-alternating-CO_2 injection in the secondary and tertiary recovery [R]. SPE 103988, 2006.