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EOR Mechanisms and Influencing Factors of CO_2-WAG Immiscible Displacement in Heterogeneous Sandy Conglomerate Reservoirs Using Nuclear Magnetic Resonance Technology

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ABSTRACT

Sandy conglomerate reservoirs are known for their tight and highly heterogeneous nature. CO_2-WAG (Water-Alternating-Gas) has been identified an effective method to enhance oil recovery of such reservoirs, while also achieving a certain amount of CO_2 storage. However, the enhanced oil recovery (EOR) mechanisms and the main controlling factors of this technology remain unclear, posing challenges in providing clear guidance for field practices.

In this paper, the CO_2-WAG displacement experiments were conducted using cores from different layers in parallel to simulate a heterogeneous reservoir and address these challenges. Nuclear Magnetic Resonance (NMR) technology was used to monitor the dynamic distribution of residual oil during the displacement process. This approach explored the EOR mechanisms of CO_2-WAG across multiple scales, including the reservoir, layer, and pore levels. Additionally, the influence of water-gas ratio and injection rates on the oil recovery at multiple scales were investigated.

The experimental results show that the overall recovery factor of CO_2-WAG flooding reaches about 24%, representing a 41.18% increase compared to pure CO_2 flooding. Analysis of residual oil changes in different layers and pore types reveals that CO_2-WAG flooding effectively inhibited early breakthrough in high-permeability layers, improved displacement efficiency in medium and low-permeability layers, and enhanced micro-displacement efficiency in medium and small pores. Moreover, the study demonstrates that increasing the water-gas ratio gradually enhances the oil recovery, primarily attributed to increased oil recovery in low-permeability layers and micropores. However, as the injection rate gradually increases, the overall oil recovery progressively decreases. This is attributed to higher injection rates resulting in earlier gas breakthrough in high-permeability layers, thereby hindering CO_2 sweep through the medium- and low-permeability layers. Conversely, the increase in displacement pressure resulting from high injection rate leads to enhanced oil recovery in the micropores.

Keywords: EOR, NMR, Heterogeneous, CO_2-WAG, Sandy conglomerate reservoir

1. INTRODUCTION

The issue of global climate change has aroused widespread concern in the international community, and it has gradually become an international consensus to reduce greenhouse gas emissions to cope with the climate challenge[1], and carbon capture, utilization and storage (CCUS) technology is one of the effective means to reduce carbon emissions, which is an important technical guarantee to achieve carbon neutrality[2].CO_2 displacement is one of the most important forms of CO_2 utilization, and CO_2 can more easily be injected into the reservoir compared with water, miscible with the crude oil, reduce the viscosity of crude oil, expand the volume of crude oil, increase the flow capacity of crude oil, and can effectively improve the recovery rate of crude oil[3-6].

As a promising CCUS technology, CO_2 enhanced recovery (CO_2-EOR) technology can also sequester CO_2 in the subsurface to achieve carbon neutrality[7-11]. However, CO_2 displacement still has many problems, such as earlier CO_2 displacement breakthrough in low

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permeability reservoirs with strong heterogeneity, more serious gas channeling, and lower sweep efficiency, which leads to low oil recovery [12-16].

CO_2-WAG displacement as an effective enhanced recovery method for heterogeneous sandy conglomerate reservoirs, combines the advantages of water displacement and gas displacement, and maintains a certain degree of injectivity while suppressing gas channeling[17-19]. However, the mechanisms and influencing factors are still unclear, and in order to investigate the enhanced recovery mechanism of this method, many experts have carried out a large number of studies.

Nezhad et al[20] (2006) investigated the effect of CO_2-WAG displacement in secondary and tertiary oil recovery after water displacement and continuous CO_2 displacement, and found that the CO_2-WAG displacement in secondary and tertiary oil recovery is effective. Masalmeh et al[21] (2023) also investigated the effect of continuous CO_2 displacement and CO_2-WAG displacement on the recovery rate in miscible and immiscible processes, and found that the recovery is more than 20% higher compared to immiscible process. The above experiments used homogeneous cores, but the reservoirs are usually heterogeneous.

In order to further investigate the recovery enhancement mechanism of CO_2-WAG in heterogeneous reservoirs, Feng Chao[22] (2012) carried out experiments on CO_2-WAG displacement in heterogeneous reservoirs, in which cores with different permeabilities were displaced in parallel, and it was found that the CO_2-WAG displacement could inhibit gas channeling of high permeability reservoirs and increase the mobilization of low permeability reservoirs; Chuang Zhao[23] (2019) conducted a large number of tests on different injection methods according to the actual carbonate reservoir conditions, and the study showed that CO_2-WAG displacement has a lower water content, which can help to delay gas channeling and improve recovery; Wang Yefei et al[24] (2021) used MRI technology to study the recovery enhancement effect of water displacement and CO_2-WAG displacement in heterogeneous reservoir, and the results showed that the heterogeneous nature of the reservoir will seriously weaken the effectiveness of water displacement, and the water displacement will not be effective in the reservoir. The results show that the heterogeneity of the reservoir will seriously weaken the effectiveness of water displacement, and that water displacement followed by CO_2-WAG displacement can improve the recovery better.

Maolei Cui et al[25] (2024) prepared vertical and horizontal heterogeneous synthetic cores, and used a high temperature and high pressure on line NMR monitoring system to monitor the characteristics of the residual oil distribution during the continuous CO_2 displacement and CO_2-WAG displacement process, clarified the specific distribution location of the residual oil, and researched and analyzed the extent of the crude oil mobilization in the different layers of the high and low permeability, but did not explore the micro-mobilization characteristics of the pore space of the CO_2-WAG displacement.

To solve the above problems, this study utilizes online NMR technology to investigate the distribution of residual oil in a multi-scale of the reservoir, the layers and the pores. On the basis of this study, the influence of different displacement methods and injection parameters on the oil recovery can be studied.

2. EXPERIMENT

2.1 Experimental Materials

The cores used in this experiment were from a sandy conglomerate reservoir, including the following three types of cores, sandy conglomerate with a permeability of about 0.1 mD, conglomerate-bearing sandstone with a permeability of about 10 mD, and coarse sandstone with a permeability of about 100 mD, respectively, as shown in Fig. 1. The water used in the experiment was heavy water with 99.8% purity (Heavy water has no signal in NMR detection, which can avoid interference with the signal of the residual oil in the measured core), with a viscosity of 1.23 mPa • s at 70℃; the gas used in the experiment was carbon dioxide; and the oil used in the experiment was crude oil, with a viscosity of 5.93 mPa·s at a temperature of 70℃.

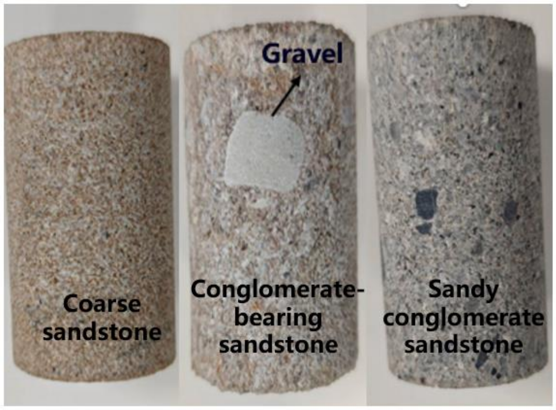

Fig. 1. The experimental cores

2.2 Experimental setup and procedure

2.2.1 Experimental setup

In order to investigate the mechanisms of enhanced recovery and microporous oil displacement mechanism in sandy conglomerate reservoirs during CO_2 and CO_2-WAG immiscible displacement, an on-line NMR monitoring displacement experiment system was established, as shown in Fig. 2.

To simulate the reservoir heterogeneity, three core holders to be connected in parallel. The displacement device mainly includes three parts of injection, monitoring and collection devices, as shown in Fig. 2. In the injection part, two VINDUM pumps are set up to control three piston-type accumulators to inject water and gas into the core by adjusting two check valves and two three-way valves to ensure stable injection of fluids. In the monitoring part, the three core holders are connected in the form of a three-way parallel connection to reflect the heterogeneity of the reservoir by connecting three different types of cores in parallel for the displacement. The inlet end of the core holders are connected with a six-way valve, and the outlet end is connected with another six-way valve. The hand pump is connected to the six-way valve to control the confining pressure and the back pressure of each core holder. A pressure sensor is installed at the upper end of the four-way valve to monitor the outlet pressure. the cores were scanned before and after the experiments using an on-line nuclear magnetic resonance (NMR) instrument to monitor the amount and distribution of residual oil. The collection part is set up with three gas-liquid separators and a gas flowmeter. The volume of oil and water can be obtained from the measurement of the gas-liquid separator, while the volume of outgassing was measured with the gas flow meter.

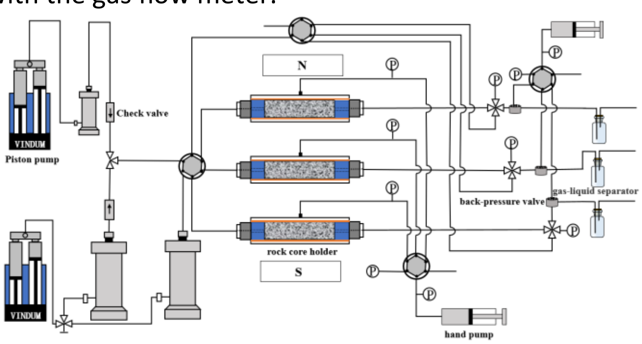

Fig. 2. Diagram of displacement experimental setup

2.2.2 Experimental procedure

Using the thin tube experiment, the minimum miscible pressure of crude oil and CO_2 was measured to be 23.1 MPa at the experimental temperature was 40°C. The experimental setup is shown in Fig. 3.

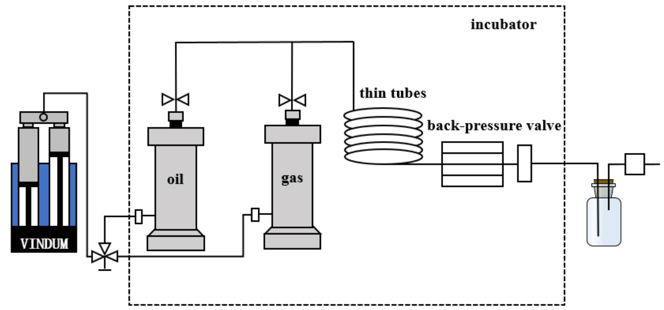

Fig. 3. Thin tube experimental setup

To investigate the EOR mechanisms and influencing factors of CO_2-WAG displacement on this reservoir under immiscible condition at the experimental pressure of 20 MPa. The experimental scheme was designed as shown in Table 1.

Table1 Experimental scheme design

Number	Water-gas ratio	Pressure/MPa	Injection rate/(ml/min)
1	Gas flooding	20	5
2	1：1	20	5
3	1：2	20	5
4	2：1	20	5
5	1：1	20	2
6	1：1	20	0.5

The specific experimental steps were as follows:

(1) The core was evacuated and then saturated with water at injection rate of 0.05 mL/min, and the amount of saturated water was calculated;

(2) Then saturated the core with oil at an injection rate of 0.1 ml/min until no water was produced at the outlet. Calculated the saturated oil volume and the saturation of the bound water;

(3) Before the start of the displacement, scanned the core with a nuclear magnetic scanner to obtain the initial oil and water distribution;

(4) Put the three types of cores into the core holders, set the back pressure and confining pressure to 20 MPa and 25 MPa, respectively;

(5) Scan the cores in real time with the NMR scanner to obtain the oil-water distribution and the oil recovery during the displacement process.

3. RESULTS AND DISCUSSIONS

3.1 CO_2 and CO_2-WAG displacement experiments

In order to investigate the effect of CO_2 and CO_2-WAG displacement on oil recovery of the heterogeneous sandy conglomerate reservoirs, this study utilizes NMR technology to investigates the effect of different displacement methods on the recovery at multiple scales of the reservoir, the layers and the pores. First of all, the on-line monitoring technology of NMR imaging was used to image the CO_2 and CO_2-WAG displacement process, so that the oil and water distribution in the core can be obtained intuitively, as shown in Fig. 4. The oil in the core is gradually extracted as the displacement proceeds, and there are still a large number of residual oil aggregates in the core after the displacement to 10 PV.

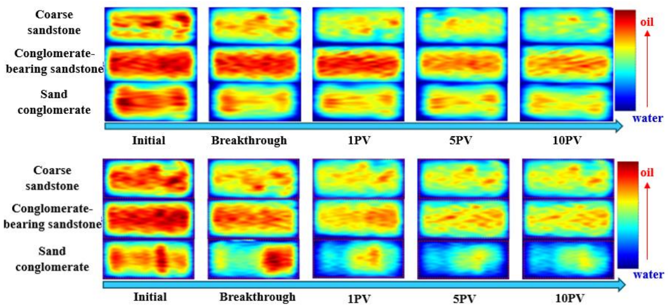

Fig. 4. Oil saturation changes during CO_2 displacement (upper panel) and CO_2-WAG displacement (lower panel, 1:1 water-gas ratio) based on NMR imaging

In this study, the dynamic T_2 spectrum during the displacement process was measured using NMR on-line monitoring technology, as shown in Fig. 5. Base on the principle of the NMR technology, it can be known that the envelope area of the T_2 spectrum is the total amount of the signal of oil in the core[26]. Base on the dynamic T_2 spectrum, it can be seen that the oil recovery of CO_2-WAG displacement is increased by 7% compared with CO_2 displacement. The oil recovery of each layer is improved, especially the sandy conglomerate layer, which is enhanced by 16%, as shown in Fig. 6. In addition, from the perspective of microscopic pores, CO_2-WAG displacement can improve the oil recovery in each pore compared with CO_2 displacement, among which the biggest improvement is for small pores, which is 8%, as shown in Fig. 7.

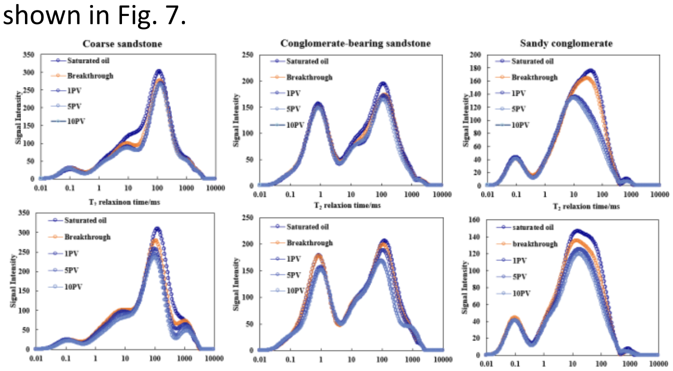

Fig. 5. Dynamic T_2 spectrum of three types of cores during CO_2 displacement (upper panel) and CO_2-WAG displacement (lower panel)

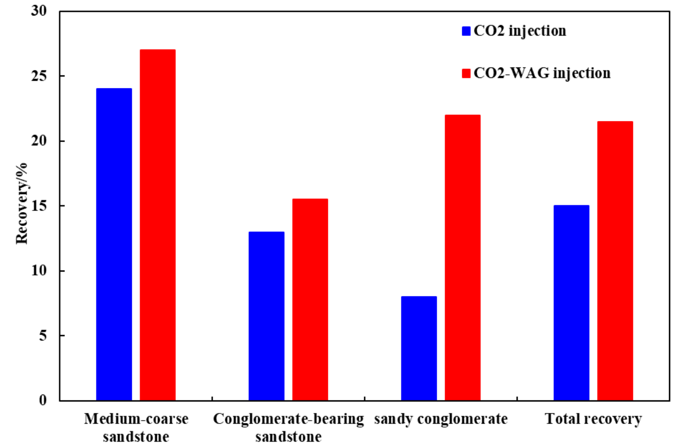

Fig. 6. Oil recovery of each layer after CO_2 displacement and CO_2-WAG (1:1 water to gas ratio) displacement

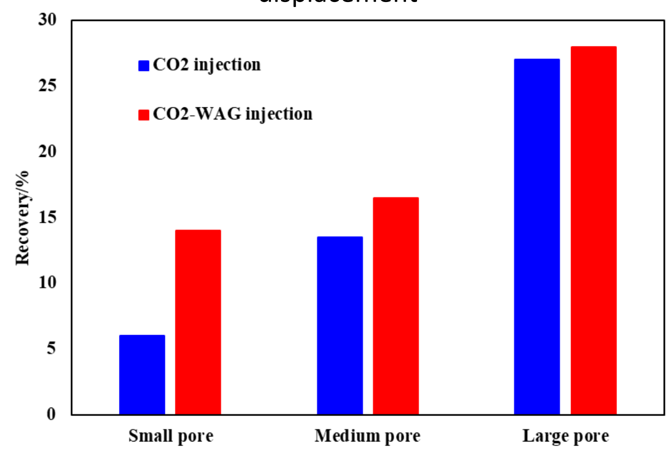

Fig. 7. Oil recovery of each pore after CO_2 displacement and CO_2-WAG (water-gas ratio1:1) displacement

3.2 Effect of the water-gas ratios on the oil recovery

In order to investigate the effect of the water-gas ratios on the oil recovery of heterogeneous sandy conglomerate reservoirs by the CO_2-WAG displacement, the distribution of residual oil in the core during the displacement process was monitored by using NMR imaging, as shown in Fig. 8. During the displacement, the oil saturation of the core gradually decreases. While the injected volume reaches 1 PV, the remaining oil is difficult to be recovered. With the increase of the water-gas ratio, the residual oil saturation decreases significantly. Moreover, the dynamic T_2 spectrum of the experimental core was monitored by on-line NMR technology, and the total recovery and the recovery of each layer under different water-gas ratios of the displacement were calculated from the T_2 spectrum, as shown in Fig. 9. The experimental results indicates that the total oil recovery is higher by the CO_2-WAG displacement compare with the CO_2 displacement. Furthermore, the study also found that increasing the water-gas ratio can improve the oil recovery of low permeability layer. From the perspective of the pore scale, the oil recovery in different pore can be calculated from the T_2 spectrum, as shown in Fig. 10. It was found that the main effect of increasing the water-gas ratio was on the enhancing the oil recovery of small pore, but it had little effect on the medium and large pores.

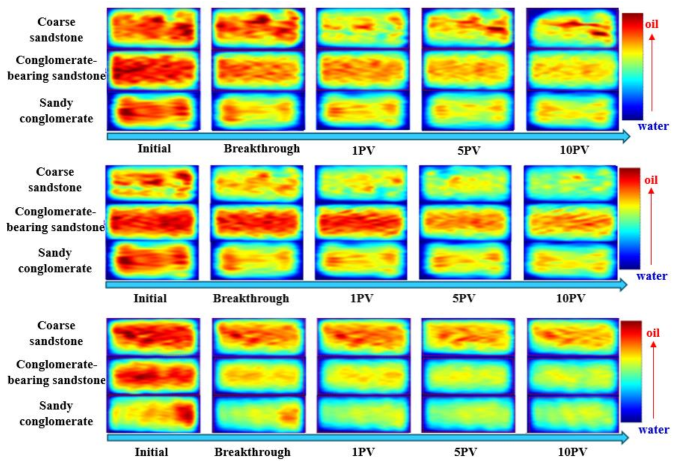

Fig. 8. Dynamic monitoring images of NMR under different water-air ratios (From top to bottom water-gas ratios of 1:2, 1:1 and 2:1, respectively)

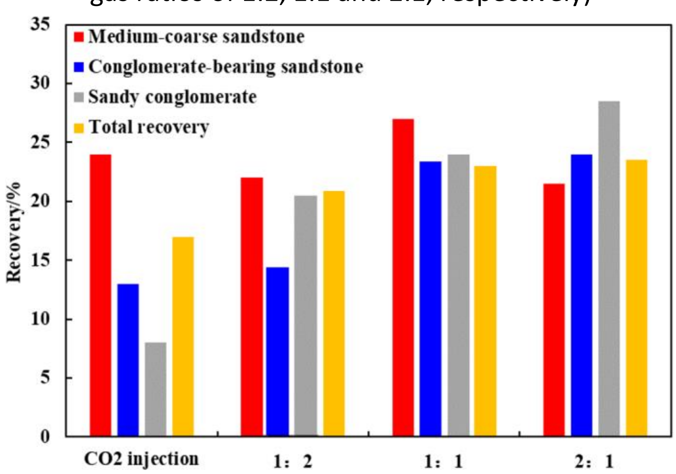

Fig. 9. Each layer and total recovery under different displacement strategies

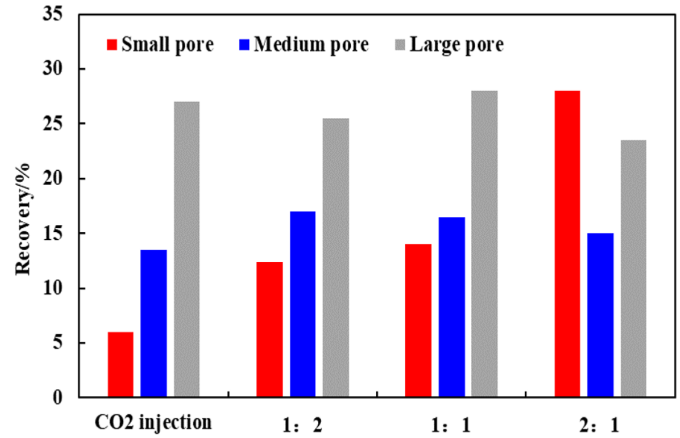

Fig. 10. Recovery efficiency of different pores under different displacement strategies

3.3 Effect of the injection rates on the oil recovery

In order to investigate the effect of the injection rates on the recovery of heterogeneous sandy conglomerate reservoirs by CO_2-WAG displacement, the distribution of residual oil in the core during the displacement was monitored by using NMR imaging, as shown in Fig. 11. During the displacement, the effect of high permeability layer displacement is more obvious, the residual oil in low permeability layer is not much change. A large amount of residual oil still exists in the core after the displacement. In addition, the T_2 spectrum of each core before and after displacement were obtained by NMR technology. The total recovery, the recovery degree of each heterogeneous layer and the pore micro-recovery under different injection rates can be calculated by the T_2 spectrum, as shown in Figs. 12 and 13. With the decrease of the injection rate, the total recovery tends to increase gradually. In addition, with the decrease of the injection rate, it can effectively inhibit the gas breakthrough in the high permeability layer and increase the recovery in the medium and low permeability layers. The recovery of the middle and large pores increases and the recovery of the small pores decreases with the injection rate decrease. This is due to lowering the injection rate can delay the breakthrough of the high permeability layer and increase the recovery of crude oil in the middle and large pores with less capillary resistance, but the lowering of the injection rate leads to a decrease of pressure gradient in the core, and the crude oil in the small pores is difficult to be driven due to the larger capillary resistance.

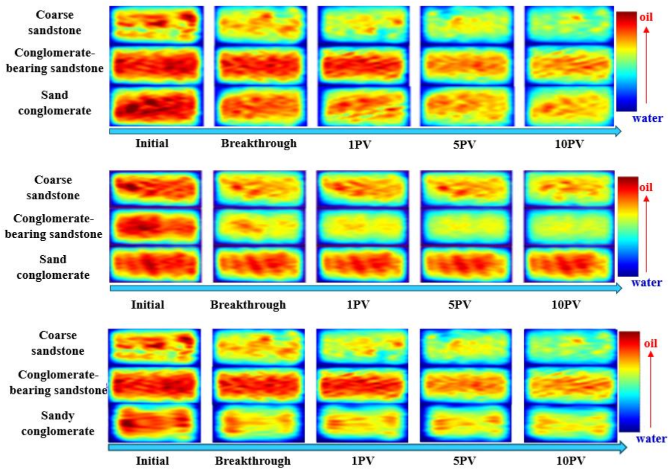

Fig. 11. Variation of oil saturation during CO_2-WAG displacement (From top to bottom, injection rate 5 ml/min, 2 ml/min, 0.5 ml/min) based on NMR imaging

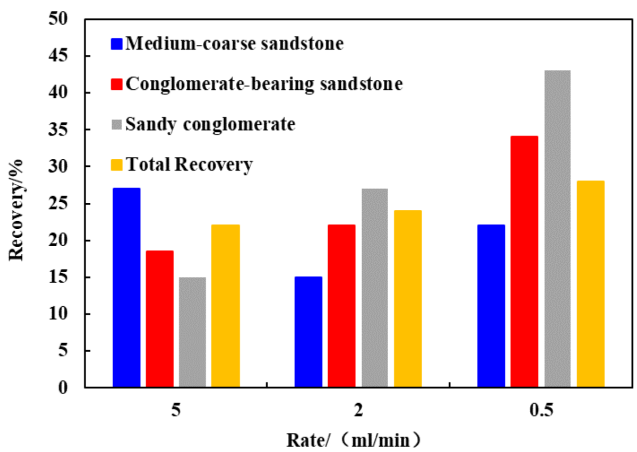

Fig. 12. Total recovery and degree of recovery of each layer for different injection rate

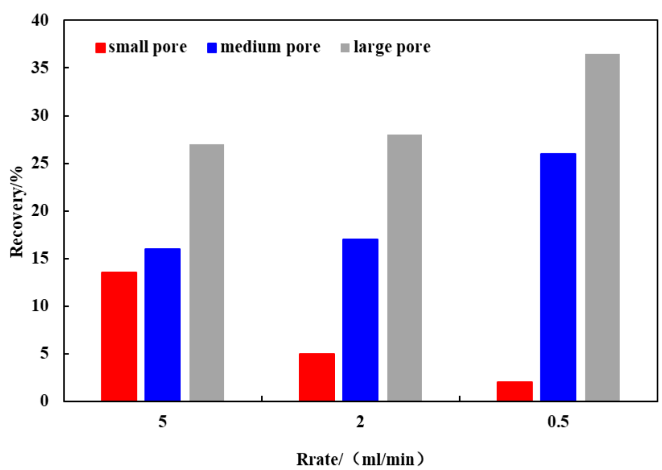

Fig. 13. Pores recovery of different injection rate

4. CONCLUSIONS

1. CO_2-WAG displacement can effectively improve the oil recovery of the heterogeneous sandy conglomerate reservoirs, especially for the oil saturated in low permeability layers and small pores.

2. Increasing the water-gas ratio of the CO_2-WAG immiscible displacement can reduces the residual oil in the low permeability layer and small pores, and enhance the oil recovery of the reservoirs.

3. Increasing the injection rate will lead to an earlier CO_2 breakthrough, reducing the recovery degree in the low permeability layer, and decreasing the micro oil recovery in both medium and large pores.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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