Energy Proceedings
Vol 53, 2025
ISSN 2004-2965

Synergistic mechanism analysis of CO_2-gravity displacement based on microfluidic and NMR experiments#

Sun Yu [1,2], Li Yiqiang [1,2*], Qi Huan[1,2], Cao Jinxin[1,2], Tang Xuechen[1,2]

1 State Key Laboratory of Petroleum Resources and Engineering, China University of Petroleum (Beijing), Beijing, China. 102249

2 College of Petroleum Engineering, China University of Petroleum (Beijing), Beijing 102249, China.
(*Corresponding Author: Yiqiangli@cup.edu.cn)

ABSTRACT

CO_2 gravity flooding is an effective method to enhance oil recovery by gas flooding. In order to clarify the synergistic effect degree of gravity differentiation and oil-gas mixing relative to EOR in the process of CO_2 gravity flooding and the oil displacement mechanism, physical simulation experiments were carried out to compare and analyze the differences of different displacement processes through microscopic visualization experiments, and to clarify the microscopic application rules. Through nuclear magnetic resonance (NMR) on-line displacement experiment, the contribution ratio of extraction degree in each level of pore throat was quantitatively divided, the lower limit of critical utilization of pore throat was defined, and the synergistic development effect was evaluated. The results show that miscibility and gravity differentiation can play a synergistic role at the same time to achieve the highest recovery rate (79.08%). Compared with immiscible horizontal CO_2 flooding, oil-gas miscible effect can reduce interfacial tension, delay gas breakthrough (0.68 PV to 0.79 PV), and lower the critical pore utilization limit (0.09 µm to 0.015 µm). The degree of utilization of pore throat under 0.1 µm was increased from 3.08% to 19.79%; Gravity differentiation can improve the transverse sweep effect during the oil and gas miscible zone moving down the displacement direction. At the same time, gravity flooding can improve the utilization degree of CO_2 on small pores by increasing the injection and production pressure difference.

Keywords: CO_2 gravity flooding; oil-gas miscibility; gravity differentiation; micropore throat mobilization.

1. INTRODUCTION

After years of water flooding development in most reservoirs, the distribution of underground fluid is complex[1-2], and the production decreases year by year. Although the content of underground remaining oil is high, the distribution is scattered and difficult to use, so it is urgent to change the development mode. Compared with water flooding, gas flooding has the advantages of strong injection capacity and wide spread range, among which CO_2 flooding has a more significant effect.

Compared with conventional gas flooding media such as N_2 and natural gas, when CO_2 is in contact with crude oil, it can exert miscible effect, dissolve and reduce viscosity, expand crude oil volume, reduce interfacial tension, etc[3-5], which can improve oil flooding efficiency. However, due to the difference of oil and gas density in the gas injection process, the problem of gas viscous fingering will occur in the oil and gas front, which will reduce the sweep efficiency. Therefore, scholars put forward the development technology of gas-inject-assisted gravity flooding (GAGD), which has the advantage that it can make full use of the gravity differentiation caused by the density difference between injected gas and crude oil to form a stable gas flooding front, inhibit viscous fingering, prolong stable oil displacement time[7], expand the spread range, and thus improve oil recovery. At present, most of the gases used in the experimental research of gas injection assisted gravity flooding are N_2, deoxygenated air and other gases with abundant air source and relatively low cost[6-8], and there are few application studies on CO_2, so it is of great significance to carry out research on CO_2 gravity flooding.

In the process of gas injection assisted gravity flooding, gravity is the main action and gas medium is the auxiliary. However, when the gas is replaced by CO_2, the oil-gas interaction mechanism changes, especially the miscible interaction between CO_2 and crude oil. In this paper, the microscopic oil displacement mechanism of CO_2 gravity flooding is studied from both microscopic and macroscopic perspectives, and the synergistic degree and mechanism of oil-gas miscibility and gravity differentiation are analyzed.

This is a paper for the 16th International Conference on Applied Energy (ICAE2024), Sep. 1-5, 2024, Niigata, Japan.

2. MATERIAL AND METHODS

2.1 Microscopic visualization experiment

The experimental crude oil was obtained from L Oilfield with a miscible pressure of 31.8 MPa. The experimental gas was CO_2 with 99% purity. Large size model (10 cm×3.6 cm) was used for normal temperature and atmospheric pressure experiments, and small size model (3 cm×3 cm) was used for high temperature and high pressure experiments. The experimental scheme is shown in Table 1, and the experimental steps are as follows:

1. The microscopic model is loaded into the high-pressure visual clamp and then vacuumed, adding the confining medium and heating the model clamp to the experimental temperature; Oil is injected into the microscopic model until the pores are filled with oil;

2. Put the glass etching chip under the high-speed camera, adjust the lens to capture clear images;

3. Connect the gas pressurization system to the displacement pipeline, increase the experimental pressure and start the displacement, the camera will shoot the whole time, and stop the experiment when the displacement no longer produces oil.

Table 1 Microscopic visualization experiment scheme

No.	*T*/℃	*P*/MPa	injection direction
1	20	0.1	Horizontal gas injection
2	20	0.1	Top gas injection
3	80	25	Top gas injection
4	80	35	Top gas injection

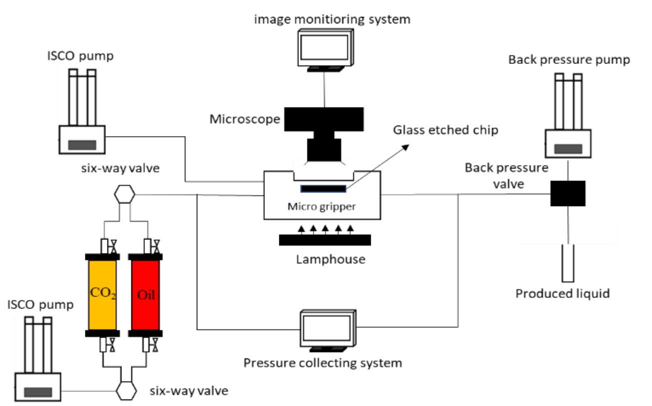

Fig. 1. Experimental flow diagram

2.2 NMR online displacement experiment

The experimental crude oil is the same as the micro-experiment part. The experimental core was taken from L Oilfield, *d*= 3.8 cm, *L*= 30 cm; The experimental gas used was CO_2 with a purity of 99%, and the experimental scheme was shown in Table 2， and the experimental steps are as follows:

1. Calibration of nuclear magnetic equipment; After the core is vacuumed for 24 h, the $MnCl_2$ solution is saturated with 20000 ppm to shield the nuclear magnetic signal in the water.

2. Establish bound water with crude oil flooding, set the experimental back pressure, continue to inject oil, raise the pressure to the required pressure of the experiment, and perform T_2 spectrum scanning;

3. Adjust the angle of the core holder according to the experimental plan, start the displacement experiment, start the nuclear magnetic T_2 spectrum scanning simultaneously, and stop the displacement until the oil is no longer produced;

Table 2 NMR online displacement experiment scheme

No.	*T*/℃	*P*/MPa	injection direction
1	80	25	Horizontal gas injection
2			Top gas injection
3		35	Horizontal gas injection
4			Top gas injection

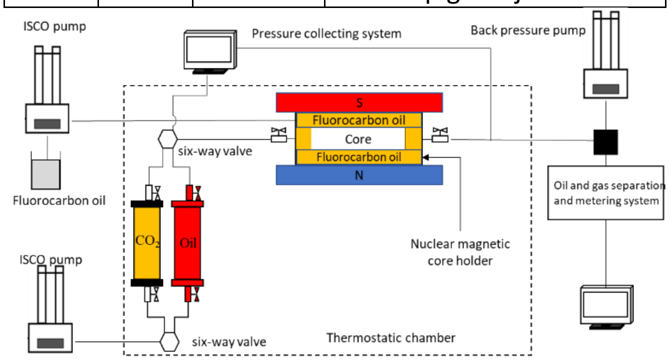

Fig. 2. Experimental flow diagram

3. RESULTS AND DISCUSSION

3.1 Microscopic visualization experiment

FIG. 3 is the microscopic experimental image of the large-size model at normal temperature and pressure. The model is placed horizontally during horizontal gas injection, and the oil-gas interface is relatively stable in the initial stage of gas injection, and fingering trend appears in the middle and right side of the model. With the progress of displacement, the stability of the oil-gas interface decreases, and the fingering on the right side increases, and the gas rapidly moves along the fingering channel to the production end, resulting in premature gas breakthrough and instability of the oil-gas interface. The regional sweep effect of the model far from the injection end is poor, the overall sweep effect is low, and the recovery rate is 37.7%. The model is placed perpendicular to the horizontal plane when air is injected at the top. At the initial stage of gas injection, the oil-gas interface moves steadily downward, and a fingering trend appears in the middle of the model. With the increase of gas injection, the CO_2 fingering in the middle of the model gradually migrated to both sides during the downward movement. Before the gas breakthrough, the regions on both sides of the model showed a fingering trend, during which the oil-gas interface still maintained a relatively stable state. At the later stage of displacement, gas channeling was formed on both sides of the model due to the weakening of gravity differentiation, and the swept area was no longer expanded, and the recovery rate was 72.8%.

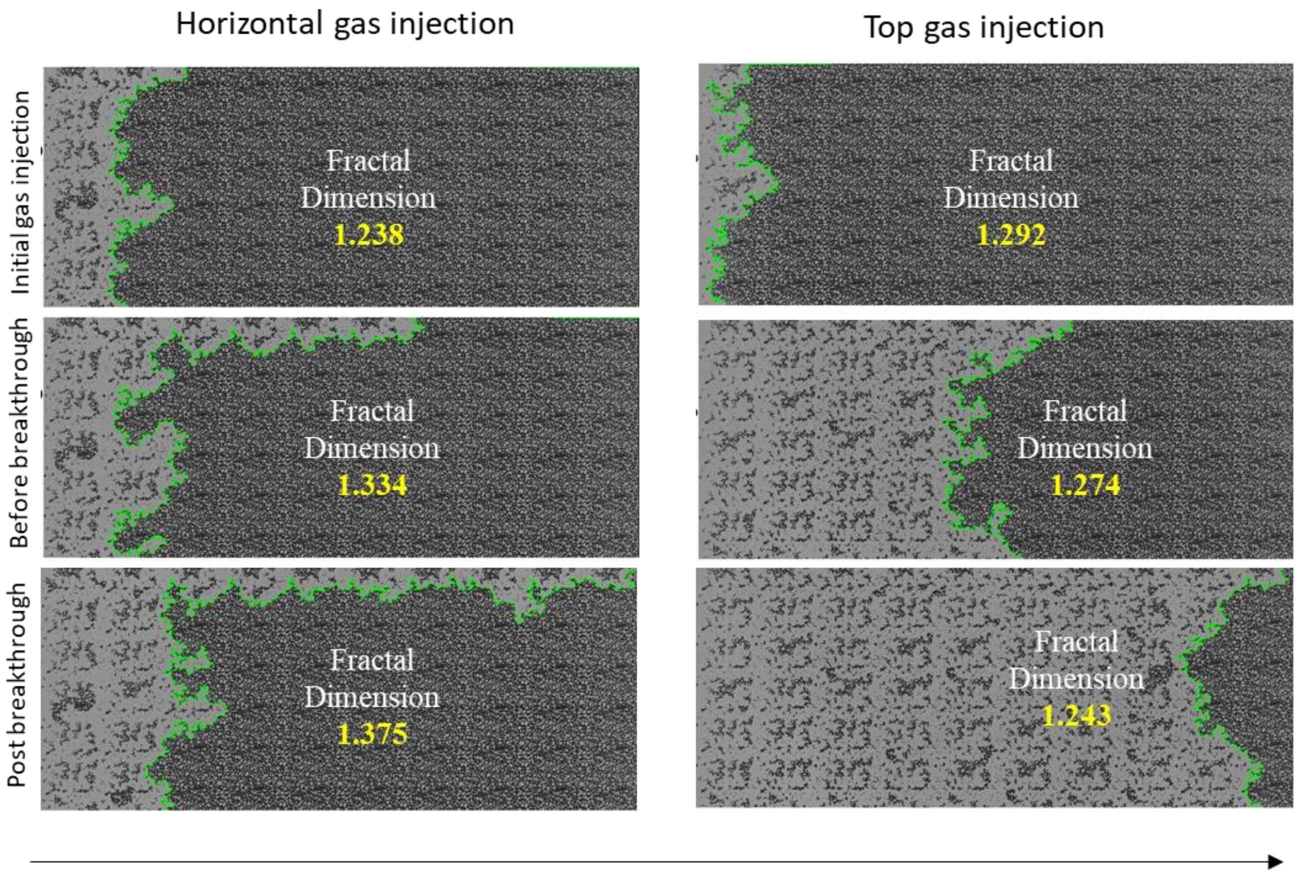

Fig. 3. Microscopic images of large scale model

It can be seen from the comparison that gas fingering occurs in the initial stage of the two gas injection methods. When horizontal gas injection occurs, gas flows along the fingering channel, and the oil-gas interface loses stability before gas breakthrough. However, top gas injection will increase the transverse sweep effect in the process of CO_2 moving down, the gas fingering degree is weak, and the sweep range is higher than that of horizontal gas injection. The fractal dimension of interfaces in different displacement stages can be calculated through image analysis of Matlab software, as shown in FIG. 3. During horizontal gas injection, the fractal dimension of the interface increases with the increase of gas injection, and the irregularity of the oil-gas interface gradually increases, that is, the degree of gas fingering becomes stronger and stronger. The fractal dimension of the interface is basically unchanged when gas is injected at the top, and the oil-gas interface is stable, which indicates that gravity differentiation can effectively inhibit the viscous fingering of gas.

FIG. 4 shows the high temperature and high pressure microscopic experiment image of a small-size model. In the process of CO_2 immiscible flooding, there is a relatively obvious gas-liquid interface between oil and gas. In the early stage of gas injection, due to the role of gravity differentiation, the oil and gas displacement interface is relatively stable, and the front fingering is low, and CO_2 first flows along the pore throat with low resistance. With the displacement process, the front fingering phenomenon appears. Due to the small size of the model, when the dominant channel is formed, the oil and gas interface is close to the production end, the gravity differentiation no longer plays a role, the CO_2 in the large pore channel breaks through to form a continuous phase, resulting in channeling, and the sweep range no longer expands. There are a large number of unswept areas in the model, and the recovery rate is

64.3%. In the process of miscible flooding, the interface between oil and gas disappears, CO_2 dissolves in the crude oil and extract the light components in the crude oil, presenting a lighter color oil and gas miscible region, reducing the viscosity of the crude oil, inhibiting the front fingering of the miscible zone, and making the front of the miscible zone more stable during the displacement process. With the increase of injection amount, the miscible zone area increases gradually and the spread range extends continuously. In the process of the formation of the main channel, due to the existence of miscible zone, while a large amount of CO_2 cross-flows, miscible effect will still promote the continuous diffusion of CO_2 to the immiscible region, and the spread range will be further expanded until the boundary of the model. The final recovery rate is 88%.

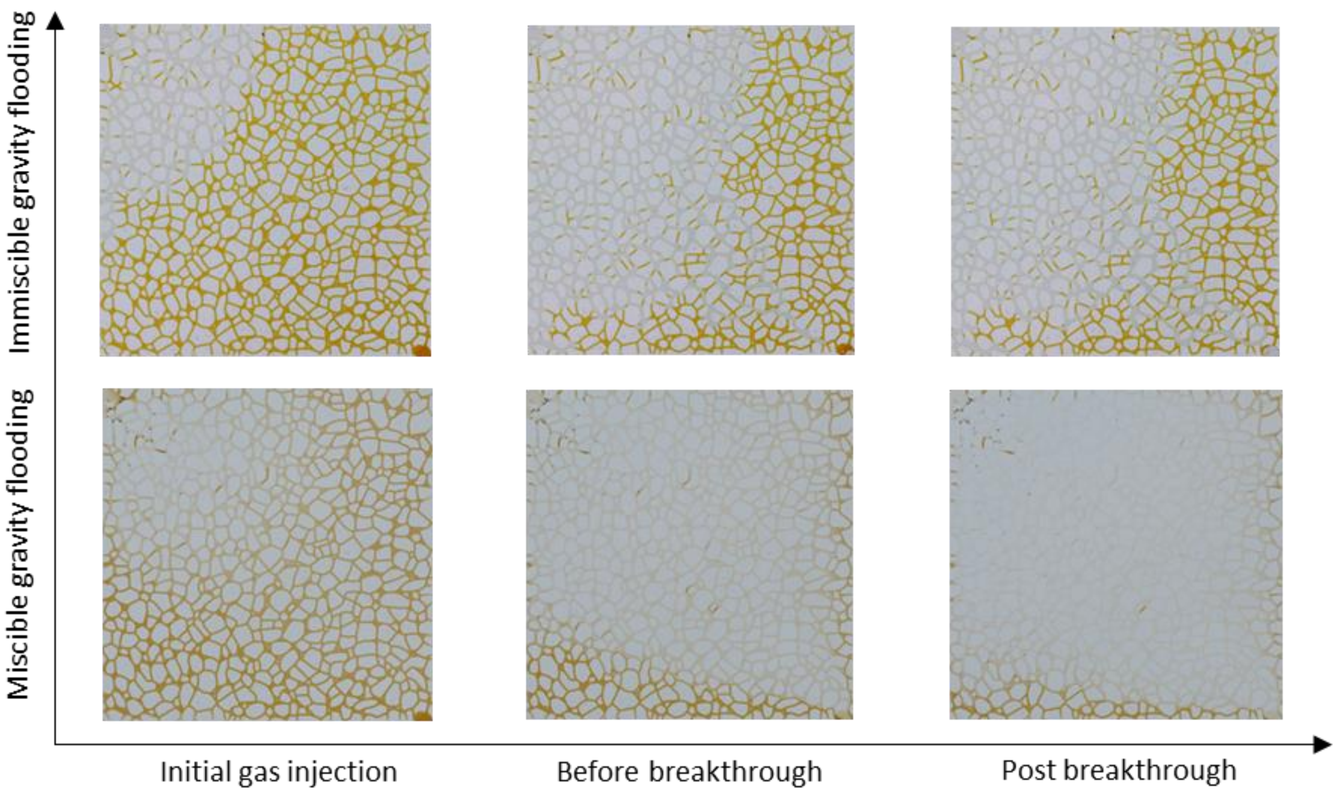

Fig. 4. Microscopic images of small size models

3.2 Microscopic visualization experiment

FIG 5 shows the results of online NMR scanning. With the increase of injection PV, the signal amplitude in the 0.1-1 μm and > 1 μm intervals decreases significantly, and the decrease amplitude of pore throat at all levels decreases gradually after 1 PV. As the gas injection pressure increases, CO_2 and crude oil reach a miscible state, and the utilization of crude oil in the pore throat less than 0.1 μm gradually increases, because the interfacial tension between CO_2 and crude oil is greatly reduced in the miscible state, and CO_2 can enter the micro-pores with greater capillary resistance, resulting in a continuous reduction of the lower limit of critical utilization. In the miscible flooding experiment, after 1 PV gas injection, the signal amplitude of pores at all levels still decreased slightly, which was due to the strong CO_2 diffusion and extraction ability under the condition of oil and gas miscible, which could continue to improve the sweep effect on small pores even after gas breakthrough. Under the same gas injection pressure, gravity differentiation improves the pressure difference at the injection-production end, so that CO_2 can enter smaller pores. The breakthrough time of miscible gravity flooding was the latest (0.79 PV), and the recovery rate was the highest (79.08%). Immiscible horizontal flooding breakthrough time is the earliest (0.68 PV) and recovery rate is the lowest (54.24%).

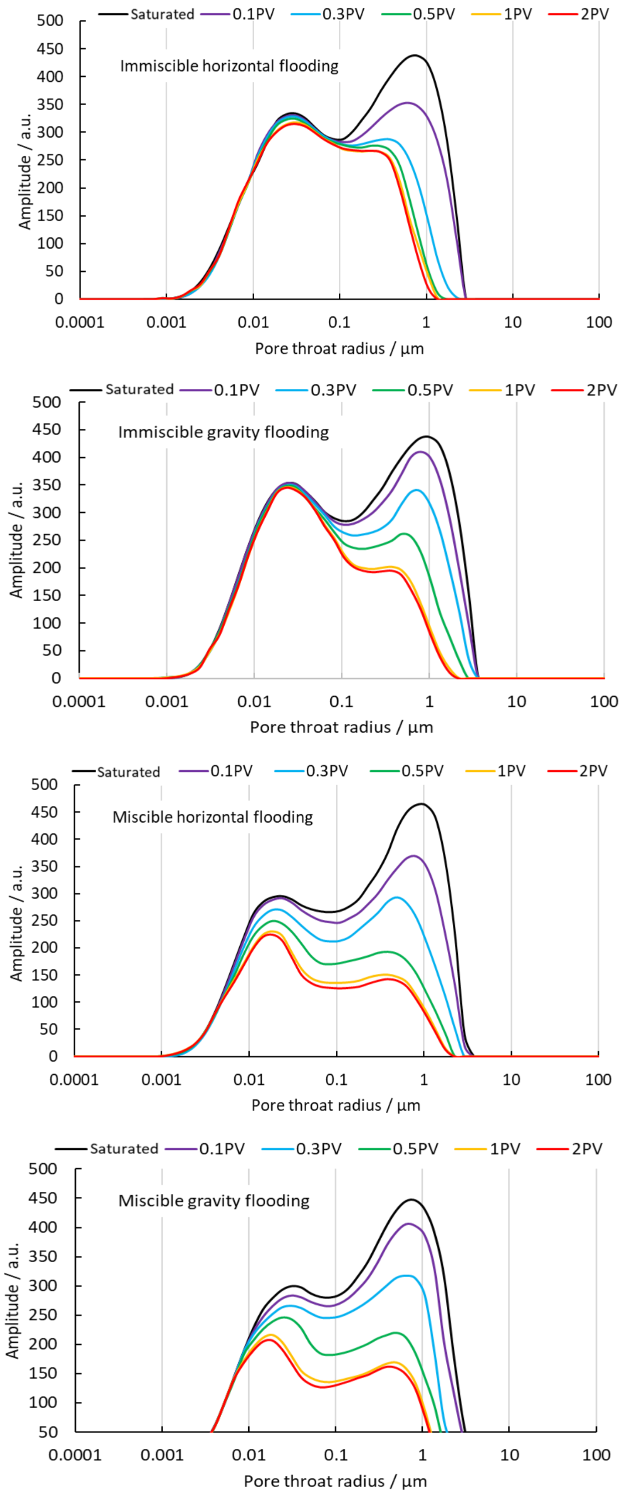

Fig. 5. Results of NMR T_2 spectrum

FIG 6 shows the contribution rate of recovery rate of each pore throat at different displacement stages. In immiscible flooding, the utilization degree of pore throat smaller than 0.1 μm is low, and the contribution of recovery rate mainly comes from pore throat larger than 0.1 μm. In miscible flooding, the contribution rate of recovery rate of pore throat less than 0.1 μm increased significantly. On the basis of miscibility, the utilization degree of gravity flooding to submicron pore-throat (< 1 μm) is further expanded, especially for pore-throat less than 0.1 μm. Under the synergistic effect of gravity differentiation and oil and gas miscibility, the contribution rate of oil recovery is the highest in the pore throat area less than 0.1 μm, which further proves that miscibility and gravity can jointly expand the utilization degree of small pores.

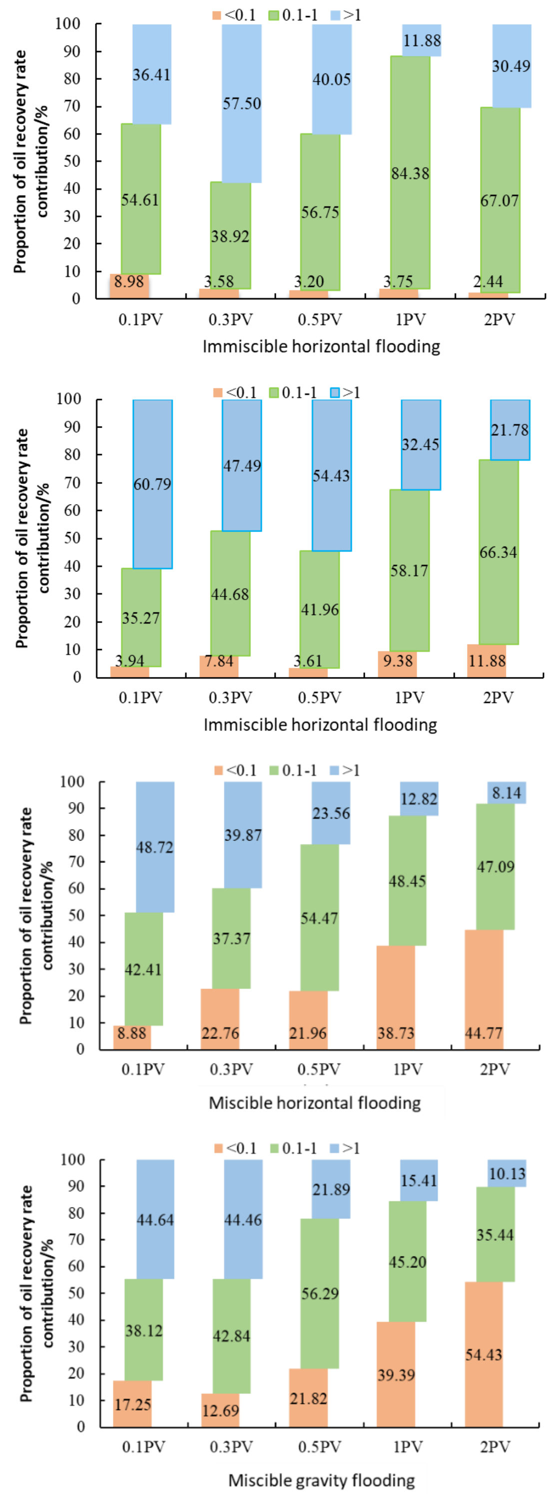

Fig. 6. Contribution of pore-throat recovery

FIG. 7 shows the dynamic change curve of the radius of critical throats. With the increase of CO_2 injected, the lower limit of critical throats utilization in pores decreases, indicating that crude oil in micropores will also be produced with the increase of CO_2 injected. It can be seen that both miscibility and gravity differentiation can reduce the lower limit of critical pore throat utilization of CO_2, and the effect of miscibility on the lower limit of critical pore throat utilization is more obvious. The final lower limit of critical utilization in miscible gravity flooding is lower than that in miscible horizontal flooding, indicating that the increase of pressure difference between injection and production by gravity differentiation and the reduction of interfacial tension between oil and gas by miscibility can synergically promote CO_2 to enter smaller pores and lower the lower limit of critical pore throat production.

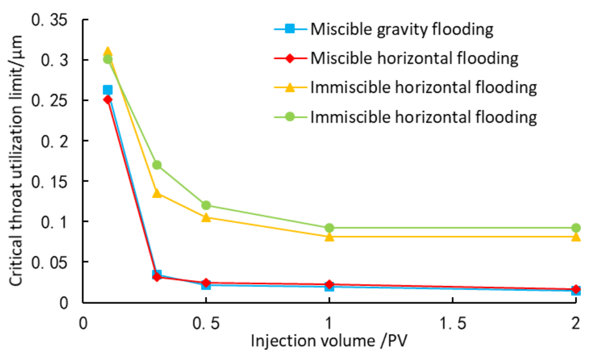

Fig. 7 Relationship between Critical throat utilization limit and pore volume

4. CONCLUSIONS

The microscopic oil displacement mechanism of CO_2 miscible gravity flooding is that the oil and gas interface can disappear to form a single phase fluid through the extraction and miscibility of oil and gas, thus improving the mobility. The horizontal sweep effect of CO_2 and crude oil miscible zone moving down the displacement direction was improved by gravity differentiation, and the sweep range was expanded. At the same time, gravity differentiation increased the injection and production pressure difference, and increased the CO_2 utilization of pore throat less than 0.1 µm (the recovery degree increased from 3.08% to 19.79%).

The miscible effect and gravity differentiation of CO_2 and crude oil can play a synergistic role at the same time, which has obvious advantages in expanding the spread of small pores (<0.1 µm) and lowering the lower limit of pore throat utilization (0.09 µm to 0.015 µm), and can achieve the highest recovery rate (79.08%).

ACKNOWLEDGEMENT

Thanks to China University of Petroleum (Beijing) for its support of this work, and sincere thanks to the anonymous reviewers.

REFERENCE

[1] Qin Jishun; Han Haishui and Liu Xiaolei. Application and enlightenment of carbon dioxide flooding in the United States of America. Petroleum Exploration and Development, 2015, 42(2): 209-216.

[2] Hu Yongle, Hao Mingqiang, CHEN Guoli, et al. Technologies and practice of CO_2 flooding and sequestration in China. Petroleum Exploration and Development, 2019, 46(4): 716-727.

[3] M A KLINS. Carbon Dioxide Flooding: Basic Mechanism and Project Design, International Human Resources Devel. Corp, Boston Ma, 1983.

[4] REZK MG, FOROOZESH J. Phase behavior and fluid interactions of a CO_2-Light oil system at high pressures and temperatures. Heliyon 2019; 5(7): e02057.

[5] BAHRALOLOM I M, BRETZ R E, ORR JR F M. Experimental investigation of the interaction of phase behavior with microscopic heterogeneity in a CO_2 flood. SPE reservoir engineering, 1988, 3(02): 662-672.

[6] Chen Xiaolong, Li Yiqiang, Tang Xiang, et al. Effect of gravity segregation on CO_2 flooding under various pressure conditions: Application to CO_2 sequestration and oil production. Energy, 2021, 226: 120294.

[7] Qi Huan, LI Yiqiang, Chen XiaoLong, et al. Low-temperature oxidation of light crude oil in oxygen-reduced air flooding. Petroleum Exploration and Development, 2021, 48(06): 1210-1217.

[8] Wang Jing, Ji Zemin, Liu Huiqing, et al. Experiments on nitrogen assisted gravity drainage in fractured-vuggy reservoirs. Petroleum Exploration and Development, 2019, 46(02): 342-353.