



Residual Oil Distribution and Displacing Mechanisms of CO₂ Asynchronous Injection and Production in Complex Fault Block Reservoirs and Pilot Test

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Abstract. The well pattern of complex fault block reservoir is not perfect, thus leading attic oil along the fault and corner oil away from the injection well and around the production well. The proposed CO₂ asynchronous injection and production (CAIP) method is expected to significantly improve the sweep efficiency and ultimate recovery factor. Firstly, the new developed physical model and experimental method for CAIP flooding are established, and the difference of recovery between this model and conventional long core model by CAIP flooding is compared, and the recovery is also compared between continuous flooding and CAIP flooding. Then, based on the microscopic visual model of longitudinal heterogeneity, the microscopic residual oil types and sweep efficiency under continuous gas injection (CGI) and CAIP injection are compared. Finally, the remain oil contact behavior in pores of different size for CAIP injection is analyzed by nuclear magnetic test. The results show that, by the CAIP injection, oil recovery can be improved by 9.2% in complex fault block reservoirs than in conventional reservoirs. And compared with the CGI flooding, the recovery of complex fault block reservoirs can be improved by 13.3% by the CAIP injection. In the longitudinal heterogeneous reservoir, the residual oil after continuous gas injection is mainly columnar and isolated type, while the CAIP injection can significantly reduce the

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columnar oil and increase the microscopic swept efficiency, leading more oil be displaced in the low permeability area near the high permeability boundary. In addition, the NMR test shows that the CAIP can not only increase the utilization ratio of large pore oil, but also contact the previously uncontacted small pore oil. The research results can provide reference for development methods of other complex fault block reservoirs of the same type.

Keywords: Fault block reservoirs · CO₂ asynchronous injection and production · Microscopic residual oil · Sweep efficiency · Oil-Gas contact

1 Introduction

Complex fault-block reservoirs are commonly of broken structure, small reserves, poor injection-production connectivity, thin oil-bearing layers, and developed interlayer, so it is difficult to form effective displacement well pattern. Irregular triangular well pattern is often adopted, or even only one-one injection and production well pattern [1, 2]. Depletion or water flooding is used to develop fault-block reservoirs under this type of well pattern, the residual oil usually includes two types: the “attic oil” formed in the area far from the injection-production percolation area due to fault sealing, and the “corner oil” formed around the production well but far from the injection well [3–5]. However, due to the imperfect well pattern in complex fault-block reservoirs, these two types of residual oil are of a higher proportion than that in integrated reservoirs, and are also the primary objects of potential exploration in complex fault-block reservoirs. At present, CO₂ flooding and storage technology is developing rapidly, due to the special mechanisms of CO₂, i.e. dissolving and expanding oil, reducing oil viscosity and interfacial tension, extraction of crude oil components, and forming miscible flooding, this technology can significantly improve oil recovery of low permeability or water-flooded reservoirs [6, 7]. Therefore, for complex fault-block reservoir, CO₂ asynchronous injection-production (CAIP) method is proposed to further enhancing oil recovery and well production for complex fault-block reservoir. The CAIP refers to “no production during injection and no production during production”. The process includes three stages: gas injection, soaking period and production, and the average pressure in the formation of three stages is always required greater than the minimum miscible pressure.

Previous studies have been carried out on the CAIP flooding. Wang Rui et al. [8] used numerical simulation methods to study the changes of the fluid flow direction in each characteristic areas in the process of the injection and production under the water asynchronous injection-production flooding. Zhang Jichang et al. [9] demonstrated that water asynchronous injection and production can extremely enhance the imbibition and oil recovery, and have strong advantages in controlling the rate of water cut increase in oil wells and excavating the residual oil in the matrix of ancient buried hill reservoirs. Yang Lei's [10] research found that water asynchronous injection and production can allow injected media to enter layers with low permeability or poor connectivity, forming a high-pressure field, effectively solving conflicts between heterogeneous layers. Cui Chuanzhi et al. [11] used numerical simulation to analyze the sweeping characteristics of CO₂ miscible flooding with CAIP and determine the characterization indicators and

classification standard of the gas channeling degree. Wang Zhilin et al. [12] found the CAIP method can tremendously inhibit gas channeling, increase the sweep efficiency macroscopically and enhancing the contact between CO₂ and oil phase microscopically, which contributes to its advantage over continuous injection.

In summary, previous studies have been mainly carried out on water asynchronous injection-production, while researches related to CO₂ injection are only limited to macro sweep efficiency and recovery performance. Researches on the CAIP mechanisms based on long core flooding, microscopic visualization simulation and NMR (nuclear magnetic resonance) test by multiple means have rarely been published, and pilot tests have not been carried out. Firstly, a physical model and experimental method are developed to simulate the characteristics of complex fault-block reservoir and its residual oil. Based on the comparison experiment between conventional long core and complex fault-block model, the effect of CAIP method in developing complex fault-block residual oil is proved, and the ability of CAIP to improve oil recovery compared with continuous gas injection (CGI) and its main mechanisms are also clarified. Then, the microscopic residual oil types of the CGI and CAIP method in complex fault-block are summarized by visual microphysical simulation, and the mechanism of residual oil development is revealed. Finally, the ability of the CAIP method to displacing the micro-residual oil in pores of different sizes was revealed using the NMR test method. And field application has proved the effect of increasing production and inhibiting gas channeling.

2 The CAIP Flooding Experiments and Section

2.1 Experimental Facility and Materials

According to the geological structure and well pattern of complex fault-block reservoir, a long core physical model which can simulate the characteristics of complex fault-block reservoir and its residual oil is designed. Compared with the conventional long core model, a short core is connected in series at the far end of the production well to simulate the corner region of the complex fault-block. The difference between complex block long core and conventional long core is shown in the Fig. 1. Then, according to the established similarity criterion, the model size is designed [13, 14].

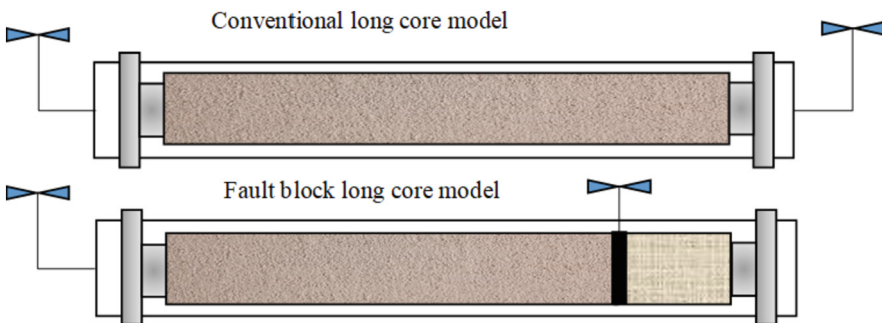


Fig. 1. Conventional long core physical model and fault block long core model

The length of the conventional long core model and the complex block model is the same. The combined core used is from low permeability outcrop, and the permeability range of the short core selected of the two models is 1.0–15.0mD. The Boolean combination method was used to form the model, the permeability of conventional long core combination is 8.51mD and the corresponding pore volume is 17.47 cm³, while the permeability of complex block long core combination is 10.85mD and the pore volume is 16.12 cm³. The core diameter is 2.5 cm. The crude oil collected from the target reservoir was used to recombine the simulation oil under the reservoir conditions by the PVT apparatus. The viscosity of crude oil was measured to be 3.64 mPa·s under reservoir conditions (P = 21.3 MPa and T = 75 °C). The total salinity of the formation water is 16262 mg/L, and the water type is NaHCO₃.

2.2 Experimental Procedure

The main steps of an CAIP experiment include: (1) The core was placed in a vacuum vessel and vacuumed with a vacuum pump for at least 48 h. Then put the core into the gripper, keep the ring pressure 1.5–2.0 MPa higher than the injection pressure, and gradually increase the back pressure to 23 MPa (formation pressure). After a period of stability, injected the simulation oil into the core until no more oil is produced. (2) Quickly injected CO₂ at 25.3 MPa (1.1 times formation pressure) into the inlet, and keep the outlet closed. After gas injection is completed, closed the valve and leave it for 2 h. Then, opened the outlet and closed port B when the outlet pressure drops to 18.4 MPa (1.0 times formation pressure). The inlet was opened for rapid CO₂ injection at 25.3 MPa (1.1 times formation pressure), then the inlet was closed and left to stand, then opened outlet for production. (3) Step 2 was repeated until the cumulative injection volume reaches 1.5 PV or the production gas-oil ratio exceeds 3000 m³/m³ to end the experiment, during which the injection volume, injection pressure, oil output and gas output are recorded in the whole course.

2.3 Oil Recovery Performance of CAIP in Fault Block Reservoirs

Based on conventional and complex fault block long-core models, the CGI flooding and CAIP flooding experiments were carried out. The experimental results are shown in Fig. 2. As can be seen from the figure, the ultimate recovery factor of CGI flooding in conventional long-core model is 57.35%, and it is 59.68% of CAIP experiment, which is 2.33 percentage points higher than continuous gas flooding. The results indicates that, for conventional long-core, when the pressure has reached miscible pressure after continuous injection, CO₂ and crude oil have been fully contacted, and the mechanisms of CO₂-EOR would be activated, then, the potential of enhanced oil recovery has been almost maximized through multi-stage contact miscible flooding. When CAIP flooding was applied, it is only equivalent to add an extra soaking process of 2 h, which had limited impact on further contact and extraction of oil-gas, and finally results limited impact on ultimate recovery factor.

However, for complex fault-block reservoirs core model, the ultimate recovery factor of continuous gas flooding is 39.25%, which is 18.10% lower than conventional core

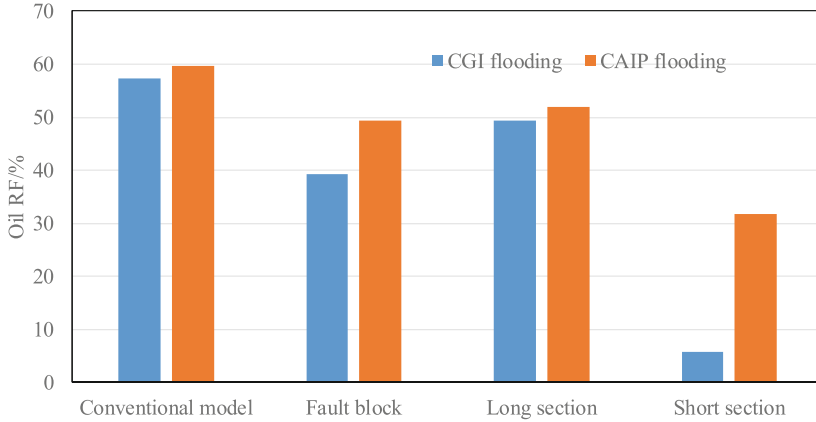


Fig. 2. Oil RF of Conventional and complex fault block models and different section under the CGI and CAIP flooding

model, and the ultimate recovery factor of CAIP method is 12.34% lower than conventional models. This shows that no matter what kind of flooding method is used, the oil recover performance of complex fault-block reservoirs would be significantly lower than conventional reservoirs, which have been verified by field test. This is because the proportion of reserves in the uncontrolled corner area of a complex fault-block reservoir is significantly higher than that in the conventional reservoir, and the swept efficiency in complex fault-block reservoir is much lower. For complex fault-block reservoirs, the CAIP method can improve the ultimate recovery by 8.09% compared with continuous gas injection, which proves the adaptability of CAIP flooding for this kind of reservoir. And it is speculated that the residual oil around the producers far away from the injector might be displaced by using AIP method. Therefore, the statistical comparison of oil displacement efficiency between long-core and short-core segments in both models were carried out, and the results are shown in the Fig. 2. The long core section represents the region between injection-production wells in the complex fault block reservoir, while the short core section represents the unswept region at the far end of the production well. As can be seen from the figure, the oil displacement efficiency of the long core section only increases from 49.3% to 52.0% under the two methods, while the oil displacement efficiency of the short core section increases from 5.75% under the continuous gas flooding method to 31.8% under the asynchronous injection-production method, indicating that the effect of the CAIP method greatly improves the reservoir at the far end of the injection-production well line, which can also displaces the “corner oil” and “fault edge attic oil” in fault block reservoirs. Hence it is one of the main mechanisms of the CAIP flooding.

2.4 Oil Production Regulations of the CAIP Flooding

The changes of displacement pressure in long-core model of complex fault block reservoir by CGI and CAIP are recorded. The cumulative gas injection volume and producing

GOR was used as the conditions for the end of the experiment, the pressure of CGI flooding was maintained between 25.2 MPa and 19.9 MPa, while the pressure of CAIP was maintained between 25.2 MPa and 18.3 MPa. From the trend of pressure change, each cycle of CAIP process goes through three stages: gas injection, well shut-in and production. During the well shut-in period (soaking period), the pressure would drop slightly due to gas dissolution and diffusion. Five cycles of CAIP process were conducted in this experiment. It can be seen that, compared with former cycles, later cycle requires more time for pressure rise in the gas injection stage and pressure drops faster in the production stage. For example, the gas injection time of the fifth cycle is 2.65 times than the first cycle, while the pressure drop time is 0.59 times than the first cycle. The analysis indicates that the later the cycle was, the higher the oil recovery be obtained, the less oil remained in the pore, and the pressure rise would be contributed by more continuous gas phase injection. Even the CO_2 is in a supercritical state, the compressibility of gas is still greater than oil, this leads to more gas injection to increase the pressure. In the production stage, firstly, a large amount of crude oil is produced, and gas phase saturation in the core is relatively large, making it easier to produce gas in large quantities; secondly, a gas seepage channel might be already formed in the core, which leads to further aggravating gas phase channeling and accelerating the pressure drop rate [15].

From the change of oil displacement efficiency of 5 cycles, the increment of oil displacement efficiency by using CAIP method for the five cycles is 16.62, 17.70, 9.25, 3.05 and 0.72 percentage points. The total recovery factor of the first three cycles is 43.57%, which contributes more than 92% of the ultimate recovery. Therefore, the first three cycles are the major recovery contribution periods of asynchronous injection and production. In the field practice, the maintenance of pressure in the former three cycles and the soaking time are all key parameters. Besides, in the field application of CAIP process, it is necessary to consider the input-output ratio and economic benefits after three cycles to formulate reservoir engineering scenario.

3 The CAIP Flooding Micro-Visual Experiments

3.1 Experimental Facility and Materials

The experimental device is a self-developed high-temperature and high-pressure microscopic visualization device. The core of the device is a high-pressure core gripper with sapphire windows, whose working temperature is 0–200 °C and the highest working pressure is 70 MPa. As shown in the Fig. 3, the digital high-speed camera used in the experiment was capable of capturing images with a full resolution of 1920×1080 . The model is a simulation model of porous media characterized by cast thin slice. The half part of the model above the injection-production line is a high permeability zone, and the lower part is a low permeability zone, which simulates the actual heterogeneity of the reservoir.

3.2 Experimental Procedure

The steps of CGI and CAIP process in microscopic visual displacement experiment mainly include: (1) Loaded the model into a high pressure core gripper, and vacuumed

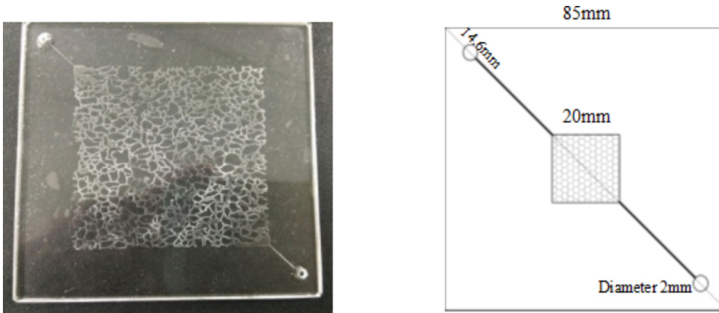


Fig. 3. Microvisual porous media model and structure

the annular space and the model simultaneously. (2) The self-imbibition method was used to saturate the annular space, and then the water saturated in the model was dyed with methyl blue. Then water was injected into the model with low pressure pump until the model is fully saturated with water. The set back pressure was slightly greater than the pump pressure, and gradually increased the pressure to the target pressure; (3) Increased the pressure of the intermediate vessel containing oil and gas to exceed the saturated pressure and saturate the model with oil; (4) The pressure in the injection section was raised to the model pressure, and gas flooding was carried out at a low and constant flow rate. When there was gas produced at the outlet, a gas flooding cycle was completed. Video recording of the process was made to record changes in key areas of visual model; The asynchronous injection-production process is the same as in Sect. 2.2.

3.3 Sweep Expansion and Oil Displacing Mechanisms for the CAIP Flooding

Image recognition and produced liquid test were used to determine the oil displacement efficiency in high permeability and low permeability areas under CGI and CAIP modes. The results show that the overall oil displacement efficiency of the vertical heterogeneous model of CAIP flooding is 58.68%, higher than that of CGI flooding (36.56%), which proves that the CAIP can significantly improve the oil displacement effect for the longitudinal heterogeneous reservoir. Meanwhile, the oil displacement efficiency of the high permeability area are nearly the same of two methods, but the oil displacement efficiency of the low permeability area is significantly different. In the case of CAIP experiment, the oil displacement efficiency in low permeability area is nearly 37% higher than that of CGI flooding, indicating that for the pore media with strong heterogeneity, continuous gas flooding mainly acts on high permeability reservoir and has limited impact on low permeability reservoir, while the CAIP can significantly expand the sweep efficiency in low permeability area.

Under CGI and CAIP mode, the fluid distribution before and after gas breakthrough in the model is shown in Fig. 4. As can be seen, in CGI process, injected gas mainly migrated forward along the high permeability zone before breakthrough, and merely entered the low permeability zone. The unswept residual oil in the high permeability zone is mainly found in the distal end of the upper section. After the breakthrough, it can be observed that the sweep area of the high permeability zone only increases slightly,

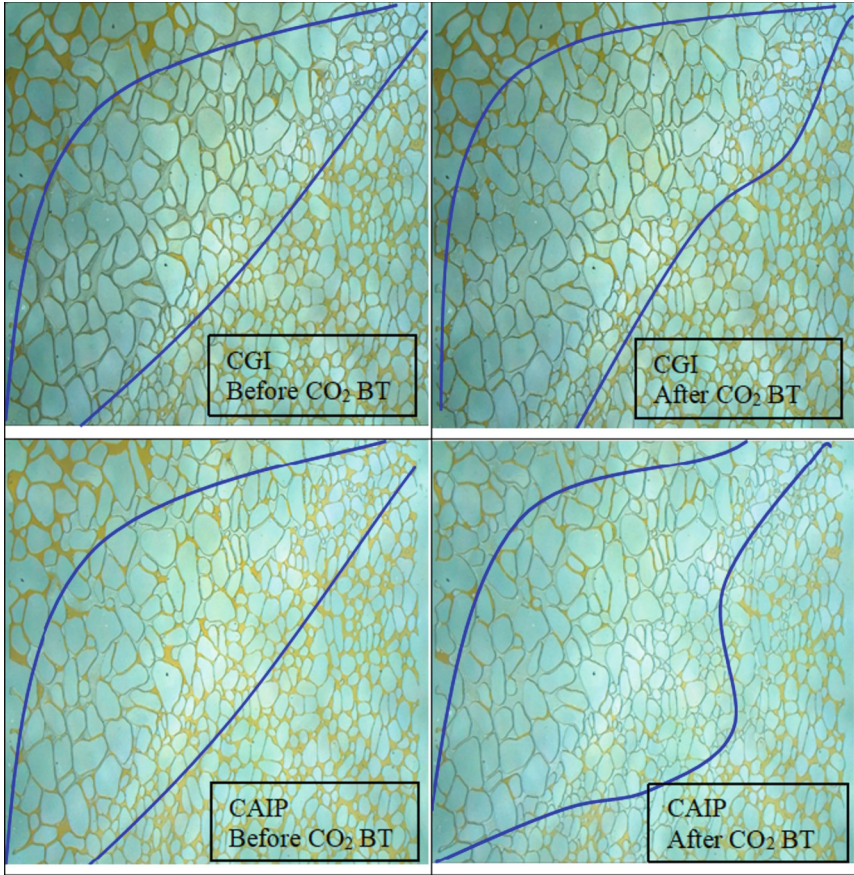


Fig. 4. Swept area of CO₂ gas phase under CGI and CAIP flooding

and a small part of the transition zone between the low permeability and the higher permeability zone is gradually swept, and the area is concentrated near the injection end and the production end. The change of the overall sweep efficiency before and after the breakthrough is not obvious. Because of the short dissolution and extraction time of CO₂ and crude oil in continuous gas flooding, the displacement effect is not ideal.

In the CAIP process, gas also mainly entered the upper area before breakthrough. Under the proposing of CAIP method, on the one hand, the spread range of the high permeability zone increases considerably, and the residual oil at the far end is also displaced; on the other hand, the crude oil in the transition zone between the upper and lower section is gradually swept, and the spread area of the low permeability zone increases significantly, which is obviously different from the CGI flooding. In addition, in the gas sweep area, due to the early gas injection and pressure increasing, the multi-stage contact between CO₂ and crude oil is fuller, the extraction and dissolution effect is stronger, and the color of the residual oil is relatively lighter, which also indicates that the oil washing efficiency of CAIP flooding is higher.

From the perspective of residual oil types, the residual oil types in the higher permeability include columnar residual oil perpendicular to the main stream line, and island residual oil caused by narrow and long throat. In the low-permeability area, because the throat is smaller, the injected gas is divided into small bubbles, which will stay in the large pores and the reduced diameter of the passageway. Due to the large resistance, continuous phase cannot be formed and it is difficult to flow, so the continuous phase of undisplaced residual oil in the throat formed by capillary force are formed. In the CAIP process, two kinds of residual oil in the low permeability area can be displaced tremendously through the pressure increasing and alternating pulse of the gas flooding.

4 NMR Tests for Microscopic Oil Displacement in CAIP Process

4.1 Principle of NMR Test

Nuclear magnetic resonance is a fast and harmless method to obtain the amount of fluid in rock pores. It mainly obtains hydrogen nuclear magnetic signals in fluid in porous media, and the signals are converted into T2 relaxation time spectra, and then inverted to obtain the distribution of hydrogen-containing fluid in different pores. By comparing the T2 spectra before and after the experiment, core displacement efficiency and porosity range can be obtained by calculation [16, 17]. Both NMR T2 spectra and capillary pressure curves can characterize the pore structure of rocks, and are also correlated. The relationship between pore radius and NMR transverse relaxation time T2 is as follows:

$$T2 = CR_C \quad (1)$$

$$C = \frac{1}{\rho_2 F_s} \quad (2)$$

where: R_c is core pore radius, μm ; C is the conversion coefficient between transverse relaxation time and pore radius ($\text{ms}/\mu\text{m}$); ρ_2 is the transverse surface relaxation rate, $\mu\text{m}/\text{ms}$, which is a characteristic parameter of rock properties. F_s is pore shape factor; T_2 is transverse relaxation time, ms.

The whole nuclear magnetic experiment process includes: non-magnetic gripper, nuclear magnetic resonance instrument, intermediate vessel, constant temperature oil bath system and injection pump. The constant temperature oil bath system is used to heat the gripper, and the circulating fluid is oil without nuclear magnetic signal. An NMR system was used to detect oil saturation in the core.

4.2 Experimental Procedure

The main test steps include: (1) Put the saturated crude oil sample into the non-magnetic gripper, connected with the constant temperature oil bath system; connected the experimental device to check the tightness according to the experimental flow chart; (2) The saturated core was scanned by NMR instrument to obtain the T2 spectral curve under the initial saturated oil condition; (3) Injected fluid to simulate the process of gas injection-soak-production successively, obtained the T2 spectrum curves of the core at each stage, and then repeat the above processes.

4.3 Microscopic Oil Displacement Mechanisms in CAIP Process

Under the CGI and CAIP method, NMR results of different injection stages are shown in the Fig. 5 and Fig. 6. As depicted in the figure, in the CGI process, after 0.4PV gas injection, the crude oil signal in the space >0.3 ms is significantly reduced, which indicates that the crude oil in the medium and large pores is effectively contacted due to pressure enhancing by gas injection and oil and gas mass transfer, but the crude oil in the small pores does not change due to the influence of capillary force. When gas injection increase to 1.0PV, the crude oil in medium and small pores could not be further displaced, indicating that gas channeling had been formed. At this time, the injected gas mainly contact the crude oil in large pores. On the contrary, in the CAIP process, in the former stage of gas injection and soaking, with the increase of microscopic pressure gradient, the CO_2 gas firstly enters the large pore, dissolves and expands the crude oil, extrudes a small part of oil into the small and medium pores, and then diffuses into the small pores, and displace a small amount of the oil. When gas injection reaches 0.4PV, the oil signal in large and small pores is greatly weakened, and the effect of gas injection is more obvious than that under CGI. In particular, the crude oil in the small and medium pores can be produced obviously, differs tremendously from that in the CGI process, which is one of the main mechanisms of CAIP flooding. Meanwhile, with further CO_2 injection, the oil in the large pores does not change, but the oil in the small pores would be further used, indicating that the residual oil in the small pores can be further displaced after gas breakthrough by the method of injection and production alternations and soaking in CAIP flooding.

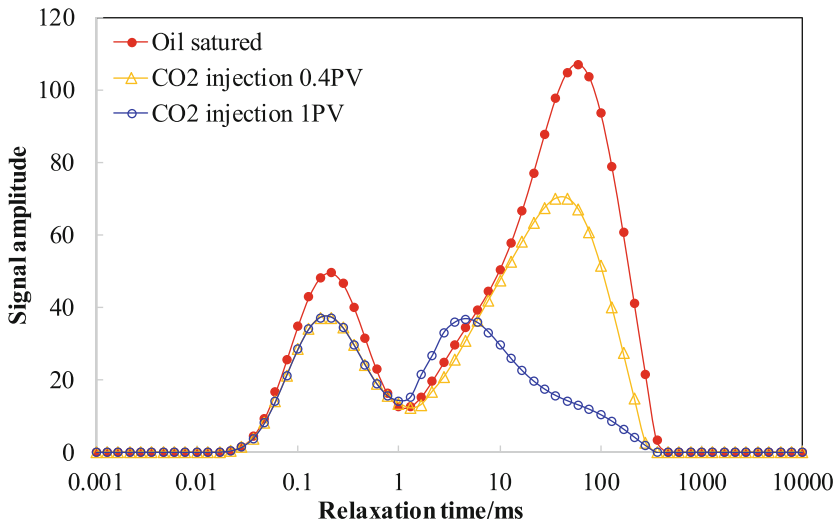


Fig. 5. The T2 spectra at different stages of the CGI process

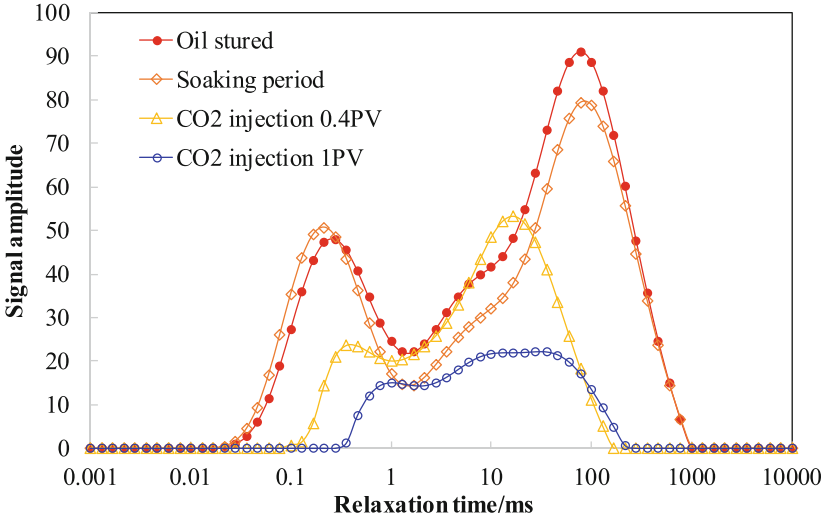


Fig. 6. The T2 spectra at different stages of the CAIP process

5 Pilot Tests for the CAIP Flooding

The average permeability of the H32 fault block is 23.6mD, the average porosity is 15.7%, the reservoir is mesoporous low permeability, the crude oil viscosity is 100.7 mPa.s, and the geological reserves are 15.1×10^4 t. The H32 block adopts the developing mode of one injection and two production wells. On February 2020, asynchronous injection and production under near-miscible pressure was implemented, two wells (H32-3, HX32) were put into production, and by the end of April 2023, the cumulative gas injection was 9161t, the total incremental oil was 6120t, the oil change rate was 0.69, and the oil

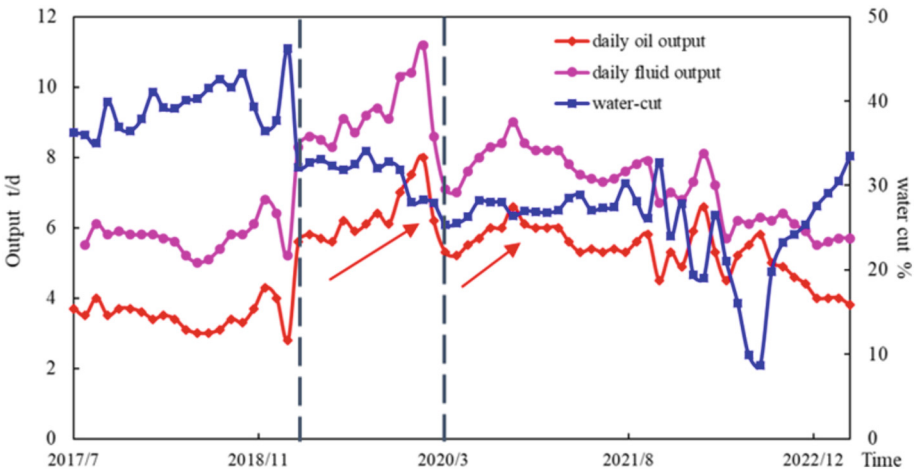


Fig. 7. The total production curve of H32 fault blocks

recovery was increased by 5.28%. Both well Hua32-3 and well X32 obtain significant oil production increase, as shown in Fig. 7. The daily oil rose to 8t/d from 3.3t/d. The effective period was up to 30 months since gas injection and the CO₂ content remained below 60%, demonstrating that the CAIP injection can also delay gas channeling and significantly improve recovery in complex fault-block reservoirs.

6 Conclusion

The developed complex fault-block reservoir physical model experiments show that the asynchronous injection-production method can significantly increase the recovery rate of complex fault-block reservoirs by more than 8%, mainly by improving the recovery of “corner oil” far from the injection well end. The contribution rate of recovery in the former three cycles of CAIP is more than 90%.

In the longitudinal heterogeneous reservoir, compared with continuous gas injection, asynchronous injection and production can increase the sweep of high permeability zone and low permeability zone by 9.3% and 33.8%, which significantly enhances the sweep effect of low permeability zone. Through shut-in pressure boost and pulse gas injection process, the production effect of residual oil formed by capillary force in the low permeability area can be displaced.

Asynchronous injection and production can displace the crude oil in the un-contacted small pores (<0.3 ms) in the continuous gas injection, and after gas breakthrough, the remaining oil in the small pores can be further excavated by suppressing single-phase gas channeling alternately through the soaking period.

The pilot experiment of asynchronous injection and production was carried out. CO₂ gas channeling was significantly inhibited and the oil recovery was enhanced by 5.28%, and the final recovery efficiency was estimated to be increased by 13.5%.

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