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Original Paper

New injection method using composite gel system and gel breaker to improve sweep efficiency and mitigate formation damage

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ABSTRACT

Polymer gels can cause damage to lowly to moderately permeable formations during both oilfield applications and laboratory evaluations of conformance treatment. To enhance reservoir sweep efficiency and oil recovery while using conventional bullhead injection, this study proposed a new injection method where a small amount of branched preformed particle gel (BPPG) was injected as a preflush slug before the injection of *in situ* cross-linked polymer gel (ISCPG). After that, a gel breaker was pumped to degrade particle gel. The breaking behavior of ISCPG and particle gels in gel breaker was first evaluated using static gel-breaking tests. Core plugging experiments combined with nuclear magnetic resonance (NMR) measurements were then employed to assess the sweep efficiency improvement and oil displacement effects of the ISCPG-BPPG composite gel system. Results showed that injecting the ISCPG-BPPG composite gel system into core samples, followed by a gel breaker, could effectively remove damage at the end faces of lowly to moderately permeable formations. Thus, it expanded the subsequent waterflood sweep volume and thus increased oil recovery by 28.43% original oil in place (OOIP). The gel breaker contained a 2:8 ratio of depolymerizing agent to ammonium persulfate at 2 wt% concentration. Moreover, BPPG in the composite gel system could act as a preflush slug to block subsequent ISCPG invasion into lowly to moderately permeable formations, reducing damage to oil-bearing formations. Compared to the single-gel injection method, the ISCPG-BPPG composite gel system demonstrated superior conformance improvement capability and oil recovery after gel-breaking treatment. The NMR technology was employed to analyze the novel conformance improvement method based on composite gel and gel-breaking mechanisms at the microscopic scale.
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1. Introduction

The ongoing development of global petroleum resources has made high-water-cut reservoirs the main focus. Due to long-term water flooding, such reservoirs exhibit intensified heterogeneity, preferential water flow paths in highly permeable formations, and inefficient mobilization of remaining oil in lowly to moderately permeable formations, resulting in an overall recovery efficiency generally below 30% (Zhu, 2023; Zhu et al., 2017a, 2017b, 2019). To improve waterflood sweep efficiency, *in situ* cross-linked polymer gel (ISCPG)-based conformance improvement technology has been widely applied in heterogeneous reservoirs (Al Brahim et al., 2022; Bai et al., 2015b; Jia et al., 2020, 2022, 2024; Pu et al., 2019; Zhu et al., 2017a). ISCPG can form highly viscoelastic gel networks in formations, preferentially plugging highly permeable channels and diverting subsequent displacing fluids to lowly to moderately permeable formations, thereby expanding sweep volume and enhancing oil recovery (Seright, 1988, 1995; Zhu et al., 2022b). However, the conventional bull-heading gel injection method has significant limitations. On one hand, excessive gelation in highly permeable formations may cause injection–production pressure imbalance. On the other hand, gel solutions can invade pores in lowly to moderately permeable formations during injection, causing irreversible permeability damage and even exacerbating reservoir heterogeneity (Bai et al., 2015a). Therefore, optimizing

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the plugging zone of gel systems and reducing formation damage risks have become primary challenges for the efficient development of high-water-cut reservoirs.

The potential formation damage caused by ISCPGs has drawn widespread attention in both academia and industry (Wu et al., 2024). ISCPG-induced damage to lowly to moderately permeable formations mainly manifest in two ways. First, ungelled solutions entering lowly permeable formations can cause near-wellbore plugging in small pores after gelation. Second, gels create rigid barriers in the face of lowly permeable zones, obstructing subsequent fluid flow (Kang et al., 2024; Liang and Seright, 2001). Seright and Brattekas (2021) found through simulation that in parallel core samples with a permeability contrast of 10, bull-heading injection of ISCPG achieved 90% plugging in highly permeable formations but also up to 47% in lowly permeable formations. Moreover, under radial flow conditions, the plugging efficiency of the lowly permeable layer reached 87%. Current evaluation methods for ISCPG damage primarily rely on core flooding tests, quantifying damage by comparing pre- and post-injection permeability changes. For example, Zhu et al. (2025) observed over 60% permeability reduction in lowly permeable cores after a single gel injection. Canbolat and Parlaktuna (2019) used CT scanning to reveal uneven gel distribution between fractures and matrix. Leng et al. (2023) combined CT scanning to show a 37.26% sweep efficiency in lowly permeable formations during ISCPG injection. However, existing research lacks dynamic monitoring of gel invasion depth and microscopic-scale analysis of damage mechanisms. Nuclear magnetic resonance (NMR) technology, through T_2 spectrum distribution, can quantitatively characterize pore fluid occurrence and gel retention characteristics (Bai et al., 2023; Deng et al., 2022; Zhu et al., 2021a). Tang et al. (2025) used NMR to analyze the conformance improvement effect of branched preformed particle gels (BPPG) in fractured reservoirs. Therefore, NMR proves to be a valuable tool for evaluating formation damage at the microscopic scale.

To address the reservoir damage caused by ISCPGs, researchers have proposed various protective control strategies. First, the injection process was optimized by using a composite system of "pre-slug + main slug". The pre-slug selectively plugs highly permeable formations, reducing the invasion of the main gel slug into other formations (Zhai et al., 2020). For example, Imqam et al. (2016) used parallel core models and found that particle gels mainly migrate through fracture channels, with minimal entry into the matrix. Second, controllable gel-breaking technologies were developed, where chemical gel breakers degrade the gel structure to restore reservoir permeability (Reddy, 2014; Zhu et al., 2021b, 2021c, 2022a, 2025). Wang et al. (2019) investigated the gel-breaking performance of different oxidative breakers on re-crosslinked polyacrylamide particle gels NaOH-activated $Na_2S_2O_8$ performed best, but no core evaluation experiments were conducted. Kang et al. (2023) also evaluated the gel-breaking performance of various oxidative breakers on ultra-high-strength gels (chromium-reinforced monomer polymerized gels). The gel breaker composed of 2%–4% NaOH + 4.5%–6% H_2O_2 could completely convert ultra-high-strength gels into an aqueous solution at 35–105 °C. Lv et al. (2023) studied the gel-breaking performance of encapsulated breakers on ISCPGs. By introducing a phenolic resin shell, the gel breaker's performance was slowly released at high temperatures. Zhu et al. (2025) found that ammonium persulfate effectively degrades phenol-formaldehyde resin-ISCPGs under reservoir conditions. Core experiments showed that gel damage in lowly permeable formations near the injection face improved to some extent after using gel breakers, but single breakers still faced issues such as uncontrollable reaction rates and pore blockage by residual byproducts. Therefore, developing composite systems that combine efficient plugging with controllable unplugging in lowly permeable zones has become a key research direction.

This study addressed the reservoir damage of traditional ISCPG conformance system in lowly to moderately permeable formations. It proposed a synergistic method combining "BPPG pre-slug + ISCPG + chemical gel breaker." BPPG (branched preformed particle gel) was selected as the pre-slug. ISCPG was cross-linked by phenolic resin. NMR technique was used to dynamically monitor gel propagation and plugging behavior in heterogeneous core samples. Finally, a compound gel breaker was designed to degrade residual gel. Core plugging experiments and oil displacement evaluations were combined to analyze the conformance improvement performance of the synergistic method, formation protection effect, and oil recovery mechanism. The study introduced a dual-protection approach combining physical barrier mechanisms with chemical degradation processes, offering both theoretical foundations and practical solutions for optimizing production in heterogeneous reservoirs with high water cut.

2. Experimental materials and methods

2.1. Experimental materials

Partially hydrolyzed polyacrylamide (XP-5, 12 million Da, 25% hydrolysis), phenolic resin crosslinker (FQ-1) with accelerator (FX-1), injection water (salinity 25,775 mg/L, pH 7.12), and oil samples (viscosity 3.96 mPa·s) were all sourced from Xinjiang Oilfield. BPPG was prepared in the laboratory, the initial particle size ranged from 1 to 3 mm with a swelling ratio of 20-fold. Ammonium persulfate (AP, AR grade, 99.5%) and deuterium oxide (D_2O, 99.9%) were from Shanghai Macklin Biochemical. The depolymerizing agent (JJ-3) was provided by Beijing Yuanyang Huanyu Petroleum Technology. Artificial three-layer sandstone core samples (gas permeabilities 100×10^{-3}, 300×10^{-3}, and 1500×10^{-3} μm^2; thickness ratios 1:3, 1:2, and 1:6) were fabricated to replicate Xinjiang reservoir conditions, as shown in Fig. 1 and Table 1. Experimental parameters and results on single ISCPG injection with gel breaker treatment in core samples can be found in literature (Zhu et al., 2025) and were used for experimental comparison in this study.

2.2. Preparation of ISCPG

The polymer solution was prepared by dispersing 1.5 g polyacrylamide in 500 mL injection water under vigorous stirring (800 ±20 rpm, 5 min), followed by reduced-speed mixing (400 ±20 rpm, 4 h). After 8-h static aging at room temperature, cross-linking components (0.2% FQ-1, 0.3% FX-1) were added under 400 ±20 rpm stirring for 20 min to generate the gelant of ISCPG system.

2.3. Gel-breaking evaluation of the composite gel system

The composite breaker system (2% total concentration, JJ-3: AP = 2:8) was prepared in formation water. Equivolumetric ISCPG and BPPG samples were introduced to the breaker solution under controlled conditions. Thermal degradation studies were conducted at 73±0.5 °C with volumetric measurements recorded half-hourly. The temporal evolution of gel volumes provided quantitative metrics for evaluating breaker performance.

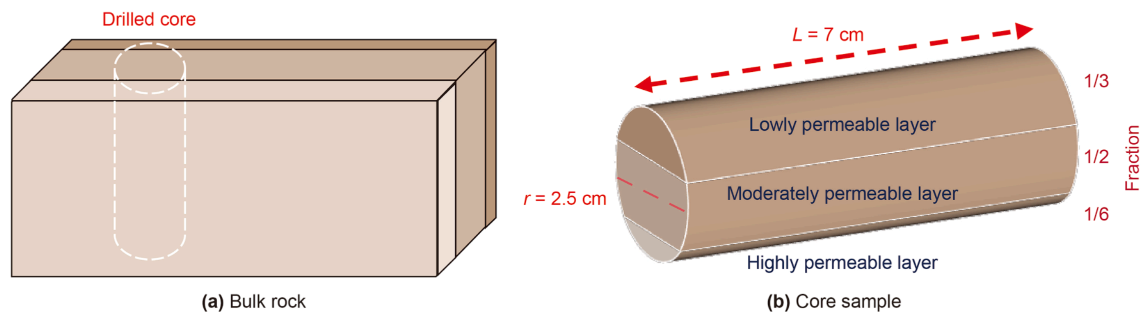


Fig. 1. Schematic diagram of the design of heterogeneous sandstone cores.

Table 1
Core parameters and experimental design.

Core No.	Length, cm	Diameter, cm	Porosity, %	Conformance agent injected
W1[a]	7.17	2.525	26.60	ISCPG
O1[a]	7.01	2.525	24.31	ISCPG
W2	6.85	2.521	26.60	BPPG + ISCPG
O2	6.93	2.518	24.51	BPPG + ISCPG

*"W" and "O" denote core samples for water-saturated and oil-saturated, respectively.
[a] Data were sourced from the reference (Zhu et al., 2025).

2.4. Plugging performance of conformance agents in core samples

The plugging performance of the composite gel system in heterogeneous core samples was assessed pre- and post-gel-breaking using core flooding tests coupled with NMR spectroscopy. As depicted in Fig. 2, the experiment commenced with the preparation of a three-layer synthetic sandstone core, which underwent vacuum saturation with injection water, followed by baseline permeability measurement through water (H_2O, with NMR signal) flooding. The NMR T_2 relaxation profile was measured to establish reference conditions. Subsequently, heavy water (D_2O, without NMR signal) was pumped to measure the injection pressure difference ΔP_1. Next, 0.2 PV BPPG and 0.8 PV ISCPG (both prepared with D_2O) were sequentially pumped into the core at a constant rate of 0.5 mL/min under controlled temperature conditions (73 °C). The core was aged for 72 h at reservoir temperature to achieve complete gelation. For the gel-breaking stage, the gelled core was vertically oriented with the injection end submerged in the gel breaker solution, maintaining a precise 1 cm penetration depth. They were treated with the gel breaker for 1 d. The final evaluation involved secondary water flooding to test the post-treatment pressure differential (ΔP_2), enabling a quantitative assessment of the system's plugging efficiency (E_P).

$$E_P = \frac{\Delta P_2 - \Delta P_1}{\Delta P_2} \times 100\% \quad (1)$$

where E_P was the plugging efficiency of the composite gel system; ΔP_1 was the pressure difference during primary heavy water flooding, MPa; ΔP_2 was the pressure difference during the injection of secondary water after gel-breaking, MPa.

2.5. Evaluation of conformance improvement and oil recovery performance for conformance agents in core samples

The effectiveness of the composite gel system in enhancing oil recovery from stratified core samples was assessed using a combination of fluid displacement tests and nuclear magnetic resonance (NMR) techniques. First, a three-layer heterogeneous artificial sandstone core sample was selected. It was vacuumed and then saturated with injection water, followed by permeability tests prior to oil saturation. The initial oil volume (V) was recorded,

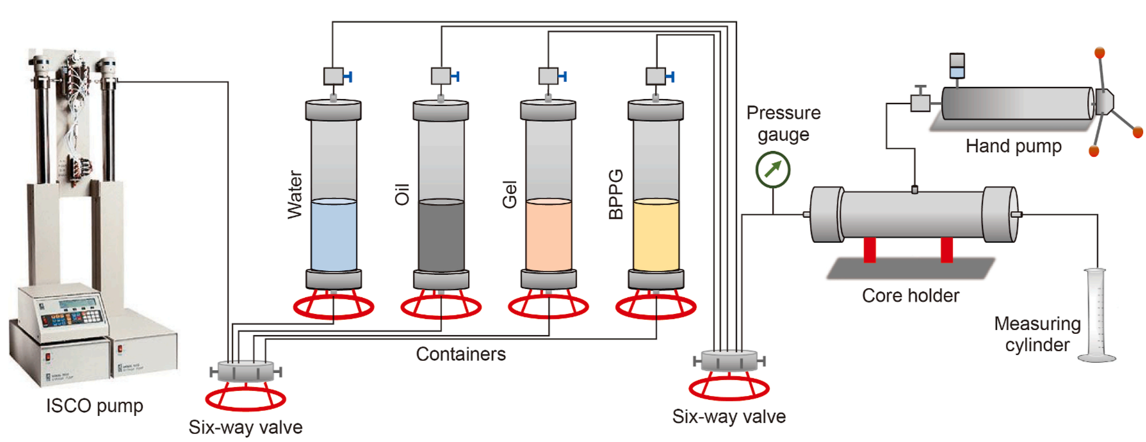


Fig. 2. Experimental schematic of the core plugging process.

and NMR T_2 spectrum analysis was performed. Heavy water was then injected, and the produced oil volume (V_1) was measured. The NMR T_2 spectrum was used to reveal the post-flooding hydrocarbon distribution across different layers. Subsequently, the core received sequential injections of 0.2 PV BPPG and 0.8 PV ISCPG (all prepared with heavy water) at a constant flow rate of 0.5 mL/min under controlled thermal conditions (73 °C), and the produced oil volume V_2 were measured. NMR T_2 spectrum analysis was then performed. The core was then aged in a temperature-regulated oven for gelation for 3 d. After that, the core's inlet was immersed in the gel breaker. The gel-breaking depth was set to be 1 cm. This chemical treatment proceeded for 24 h before executing the secondary heavy water flooding phase, where collected oil volumes (V_3) enabled computation of the ultimate recovery efficiency (E_R) as follows:

$$E_{\mathrm{R}} = \frac{V_1 + V_2 + V_3}{V} \times 100\% \quad (2)$$

where E_R is the oil recovery efficiency; V and V_1 are the initial oil content in the heterogeneous sandstone core and the volume of oil recovered during the first heavy water flooding, respectively, mL; V_2 and V_3 are the oil production volumes during the composite gel injection and secondary water flooding, respectively, mL.

2.6. Sweep efficiency evaluation based on online NMR analysis of core samples

By measuring the NMR signal amplitude of hydrogen nuclei in the fluids within core samples, the distribution and content of fluids in pores of different sizes could be determined. The core NMR analyzer (SPEC-RC035, Beijing SPEC Co.) was employed to measure the T_2 signal amplitude of core samples at various displacement stages. The T_2 spectrum curves were obtained for core samples at different displacement stages, including water saturation, oil saturation, primary heavy water flooding, after gel injection, and secondary heavy water flooding. The NMR measurement parameters were selected as follows: pulse interval (TAU) 100 μs, sampling interval (DW) 4 μs, number of scans (SCAN) 32, and signal gain (RG) 5 dB.

3. Results and discussion

3.1. Static degradation performance for the composite gel breaker

The static degradation performance of the composite gel breaker on ISCPG and BPPG was evaluated through static gel-breaking experiments. This study used a composite gel breaker at a predetermined 2:8 mass ratio of gel breaker (JJ-3) to ammonium persulfate, with a total concentration of 2%. The experiments were conducted at 73 °C. The static degradation performance was analyzed by monitoring real-time volume changes during the gel-breaking process. Comparative photographs of the ISCPG and BPPG before and after undergoing 5-h exposure to the composite solution are shown in Fig. 3.

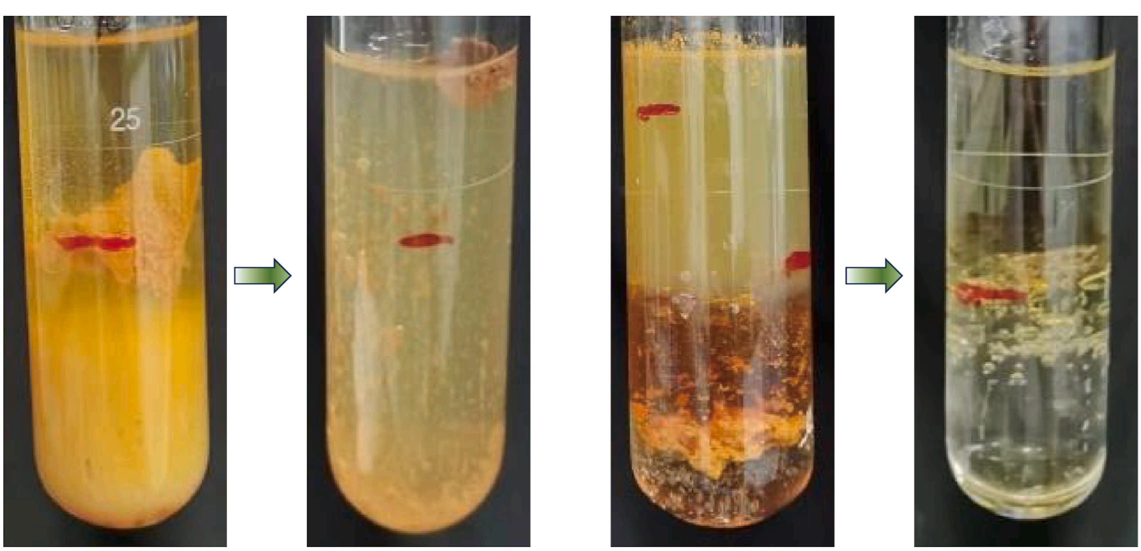
As shown in Fig. 3, the ISCPG underwent substantial degradation when treated with the gel breaker. The experimental results demonstrated highly effective gel degradation, with the cross-linked polymer network of ISCPG being almost entirely disintegrated, leaving only trace amounts of undissolved material. BPPG demonstrated even better gel-breaking performance, achieving complete degradation with nearly zero residual particles in the test tube.

3.2. Conformance improvement by composite gel system in water-saturated cores

3.2.1. Displacement performance of composite gel system in water-saturated cores

The core plugging experiments evaluated the injection and plugging capability of the composite gel system. 0.2 PV BPPG and 0.8 PV ISCPG were sequentially pumped into the core sample at 0.5 mL/min under 73 °C, with NMR T_2 spectra analyzing their injection and plugging behavior. Continuous monitoring of injection pressure variations was implemented during all experimental stages to assess flow behavior, as shown in Fig. 4.

As shown in Fig. 4, when sequentially injecting 0.2 PV BPPG and 0.8 PV ISCPG into water-saturated heterogeneous core samples, the pressure difference during injection increased significantly. The injection pressure drove to peak at 18.19 MPa during the



(a) ISCPG **(b)** BPPG

Fig. 3. Comparison of ISCPG and BPPG before and after 5 h of degradation in the composite solution.

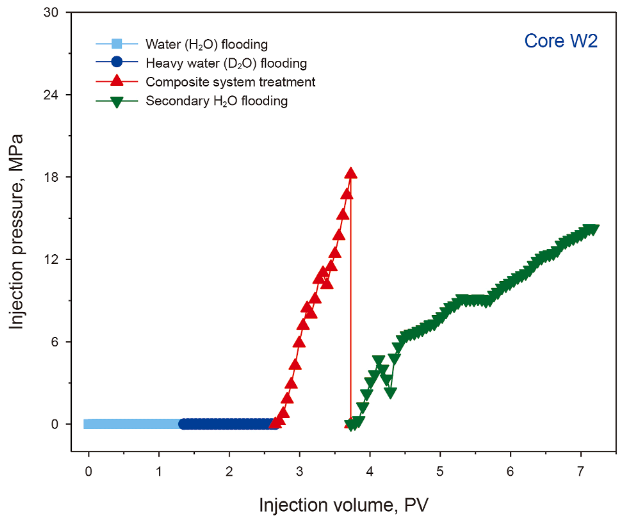


Fig. 4. Injection and plugging pressure dynamic curves of composite gel system in water-saturated heterogeneous core.

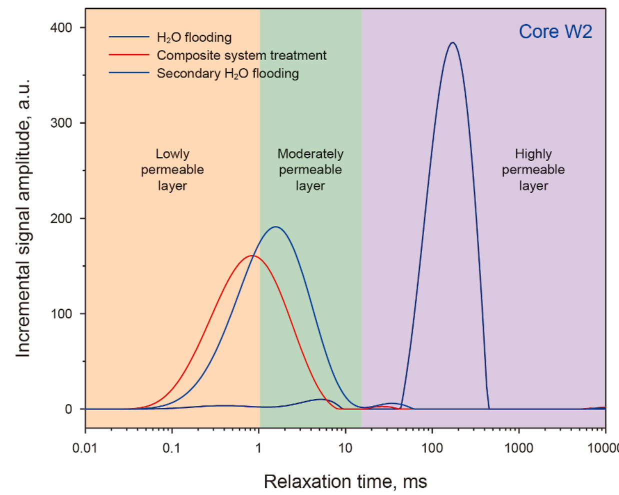


Fig. 5. T_2 dynamic curves of injection and plugging for composite gel system in water-saturated heterogeneous core.

injection of the ISCPG-BPPG composite gel system, and 14.24 MPa during secondary water flooding. This indicated that the composite gel system could effectively plug core pores, improved sweep efficiency, and demonstrated high plugging efficiency and conformance improvement capability. After gel breaking treatment using the composite gel breaker, the secondary water flooding injection pressure decreased, suggesting this system can partially mitigate damage to lowly permeable zones caused by the composite gel system, thereby protecting oil-bearing zones.

3.2.2. Conformance improvement capability of composite gel system in water-saturated cores

The conformance improvement capability of the composite gel system in water-saturated core samples was investigated using NMR T_2 spectrum analysis. This study examined the injection and plugging performance from the perspective of rock pore structure characteristics. A multi-stage NMR analysis method was employed, where core samples were tested after three displacement stages: water flooding, gel injection (prepared with D_2O), and secondary water flooding. NMR signal acquisition and data processing yielded the T_2 spectra shown in Fig. 5. Comparative analysis was conducted between cores treated with single gel (ISCPG) injection (Zhu et al., 2025) and those treated with the ISCPG-BPPG composite gel system, with their T_2 spectrum comparison curves presented in Fig. 6. NMR signals were also compared between cores treated with single gel injection and the composite gel system after secondary water flooding, analyzing different impacts on water flooding performance. The corresponding T_2 spectrum comparison curves are shown in Fig. 7.

As shown in Fig. 5, the NMR signals after primary water flooding predominantly appeared in highly permeable zones. After sequentially injecting 0.2 PV BPPG and 0.8 PV ISCPG into water-saturated heterogeneous core samples, a remarkable redistribution occurred—the NMR signals became predominantly localized within medium to low permeability zones. The NMR signals after secondary water flooding also concentrated in lowly to moderately permeable zones. This indicates that primary water flooding preferentially accessed highly permeable zones, the composite gel system successfully altered this flow behavior. The system's ability to selectively plug highly permeable channels forced subsequent injected fluids to penetrate previously underutilized lowly to moderately permeable formations, thereby significantly improving volumetric sweep efficiency and enhancing hydrocarbon recovery from these typically poorly swept reservoir sections.

Fig. 6 shows that NMR signals from both the single gel (ISCPG) injection and the ISCPG-BPPG composite gel system treated cores were mainly distributed in lowly to moderately permeable zones. However, the composite gel system exhibited greater peak NMR signal amplitude and greater cumulative signal amplitude than the single gel system. It indicated that while both systems can effectively plug highly permeable zones and improve oil recovery in lowly to moderately permeable zones by enhancing sweep efficiency, the composite gel system demonstrated superior conformance improvement performance. It was due to the fact that BPPG presented higher injection difficulty than ISCPG, resulting in significantly mitigated migration into lowly to moderately permeable zones, thereby minimizing formation damage. It also effectively plugged subsequent ISCPG from entering these layers, providing reservoir protection. These findings confirmed that the composite gel system offered better conformance improvement performance while effectively reducing reservoir damage.

As shown in Fig. 7, after treatment with either single ISCPG injection or the composite gel system followed by secondary water flooding, the NMR signals of the core samples were mainly concentrated in the lowly to moderately permeable zones. However, the peak NMR signal amplitude and cumulative signal amplitude were greater for the composite gel system. For the composite gel system, the blocking effect of BPPG effectively restricted further migration of the ISCPG into lowly to moderately permeable zones. This allowed the gel breaker to act more thoroughly at the injection end of the core, reducing formation damage in lowly to moderately permeable zones and improving sweep efficiency. These results further demonstrated that the composite gel system provided better conformance improvement and reservoir protection.

3.2.3. Mechanism analysis of conformance improvement for composite gel system

The conformance improvement mechanism of the ISCPG-BPPG composite gel system was comprehensively revealed by combining injection pressure dynamics and NMR T_2 spectra, and compared with the single ISCPG system. The comparative mechanism diagram of single ISCPG and composite gel system is shown in Fig. 8.

As shown in Fig. 8, both the single ISCPG injection and composite gel systems preferentially migrated into the highly

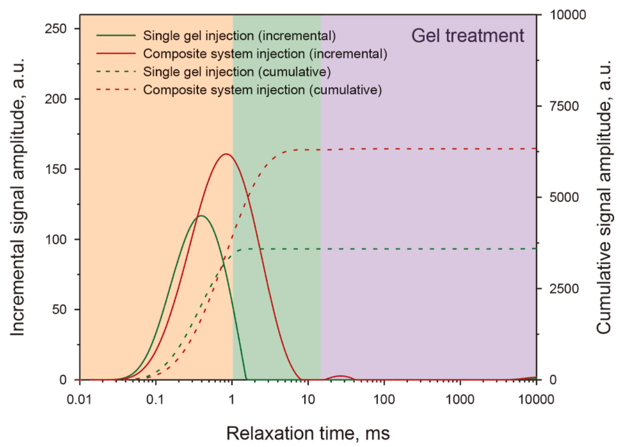


Fig. 6. Comparison of NMR T_2 spectra of different conformance improvement systems in water-saturated core samples. Data for single ISCPG injection was sourced from Zhu et al. (2025).

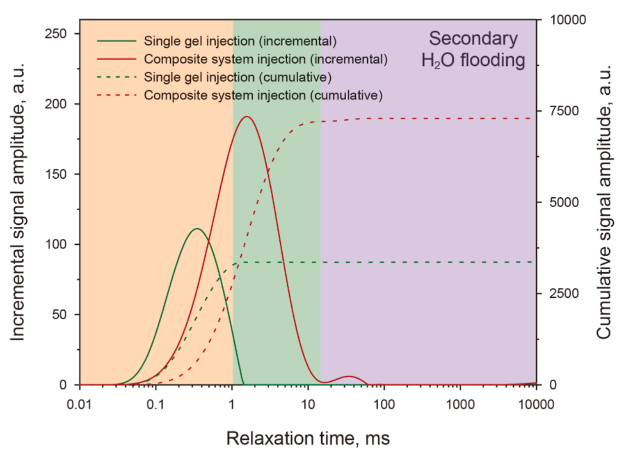


Fig. 7. Comparison of NMR T_2 spectra of different conformance improvement systems in water-saturated core samples after secondary water flooding. Data for single ISCPG injection was sourced from Zhu et al. (2025).

permeable zones of the core during injection, forming effective plugging in these zones. This altered subsequent water flooding flow paths and improved sweep efficiency. However, a portion of both gel systems inevitably penetrated into moderately and lowly permeable zones of the core matrix. This unintended invasion resulted in some impairment to oil-bearing zones without necessitating additional plugging, thereby reducing conformance improvement effectiveness. In contrast, the ISCPG and BPPG in the composite gel system demonstrated significant synergistic effects. Since BPPG were more difficult to inject than ISCPG, their migration into lowly to moderately permeable zones was relatively limited, thus minimizing damage to non-target formations. Additionally, the injected BPPG acted as barriers, effectively preventing further ISCPG invasion into lowly to moderately permeable zones while enabling more thorough gel-breaking treatment. It enhanced sweep efficiency while minimizing reservoir damage.

3.3. Oil displacement and sweep performance by composite gel system and gel breakers

3.3.1. Analysis of oil displacement dynamics in the composite gel system

The displacement efficiency of the ISCPG-BPPG composite gel system was analyzed through displacement experiments using oil-saturated, three-layer heterogeneous cores. Real-time monitoring captured variations in injection pressure along with detailed records of oil and water production from the effluent. The experimental results are shown in Fig. 9.

As illustrated in Fig. 9, when 0.2 PV BPPG and 0.8 PV ISCPG were sequentially pumped into the oil-saturated heterogeneous core samples, the injection pressure exhibited a substantial rise. The experimental results revealed a significant pressure differential between injection stages, with the composite gel system achieving a peak injection pressure of 13.85 MPa compared to just 1.63 MPa during secondary water flooding. The treatment demonstrated remarkable effectiveness, improving oil recovery from an initial 23.91% during primary water flooding to 52.34% after gel placement—a substantial 28.43% increase in original oil in place (OOIP). It indicated that the composite gel system successfully plugged highly permeable zones, improved sweep efficiency, and thus enhanced oil recovery.

Table 2 shows that both the single ISCPG system and the composite gel system positively affected oil recovery during conformance improvement but with different improvement levels. The post-plugging recovery increased by 18.75% OOIP for the single gel system and 28.43% OOIP for the composite gel system, which was significantly higher. It demonstrated that the composite gel system provided better conformance improvement and superior oil production enhancement compared to the single ISCPG system.

3.3.2. Analysis of sweep efficiency enhancement by composite gel system

NMR T_2 analysis was employed to study the conformance improvement effect of the composite gel system in oil-saturated core samples and its impact on sweep efficiency, as shown in Fig. 10. Further comparison was made between the NMR signals of cores treated with a single ISCPG injection (Zhu et al., 2025) and those treated with the composite gel system (i.e., BPPG + ISCPG).

Fig. 10 shows that in the heterogeneous sandstone core after oil saturation treatment, the majority of NMR signals were concentrated in highly permeable zones. After sequentially injecting 0.2 PV BPPG and 0.8 PV ISCPG into the heterogeneous core saturated with oil, a noticeable reduction in NMR signals was observed within the highly permeable zones. It manifested that the composite gel system primarily entered highly permeable zones, effectively plugging the dominant water flow channels. Consequently, subsequent heavy water flow was diverted to previously unswept areas, enhancing sweep and oil recovery efficiency.

The comparative NMR T_2 spectra curves of these two gel systems are presented in Fig. 11. Additionally, the NMR signals of cores treated with both gel systems after secondary heavy water flooding were also compared, as shown in Fig. 12.

As depicted in Fig. 11, the cumulative NMR signal amplitude in the highly permeable zones treated with the composite gel system was greater than that of the single ISCPG system, while the cumulative NMR signal amplitude in the lowly permeable zones was lower. It indicated that the composite gel system migrated more extensively in the highly permeable zones, effectively plugging the highly permeable channels. At the same time, the composite gel system demonstrated selective migration behavior, exhibiting limited penetration into moderately and lowly permeable zones while maintaining effective plugging in highly permeable regions. This selective plugging effect reduced overall formation damage compared to conventional single-ISCPG methods while maintaining effective plugging in the highly permeable zone blockage.

Fig. 12 shows that the core exhibited a greater cumulative NMR signal amplitude in the highly permeable zones compared to the

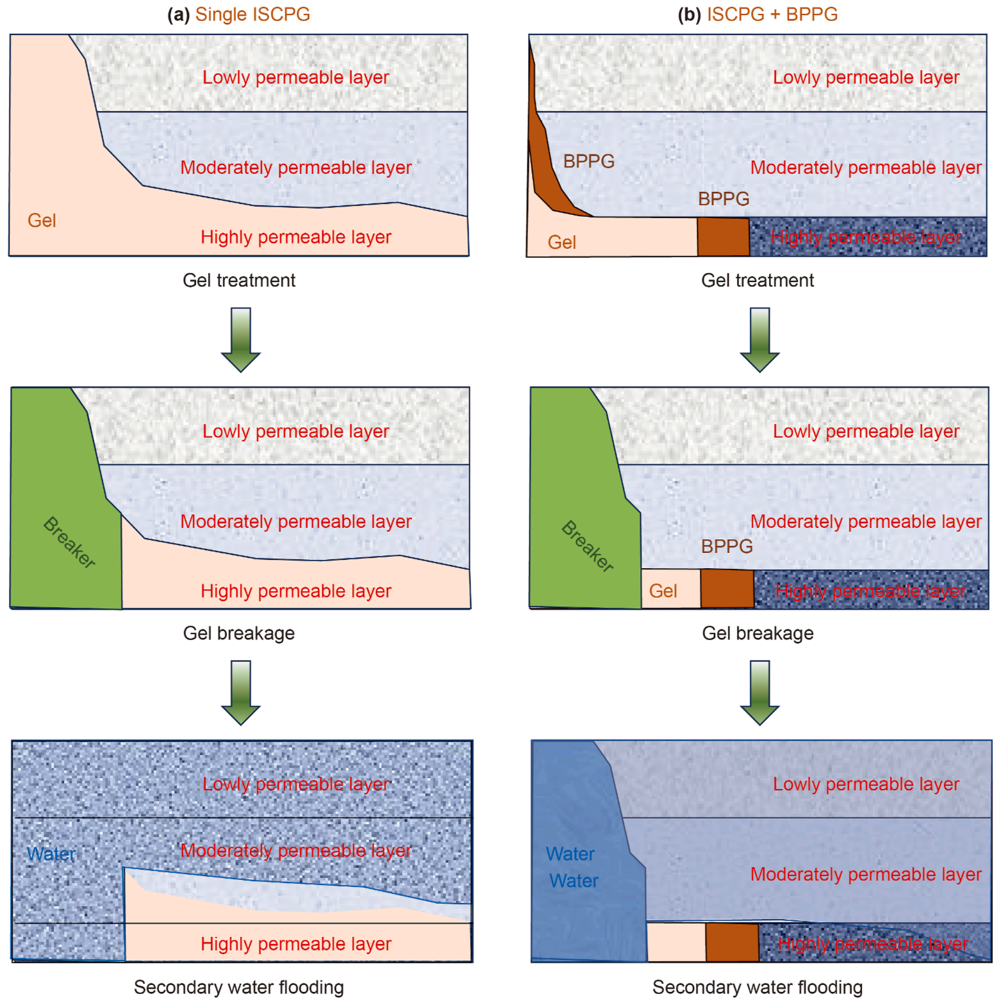


Fig. 8. Comparison diagram of conformance improvement mechanisms for single ISCPG and composite gel system.

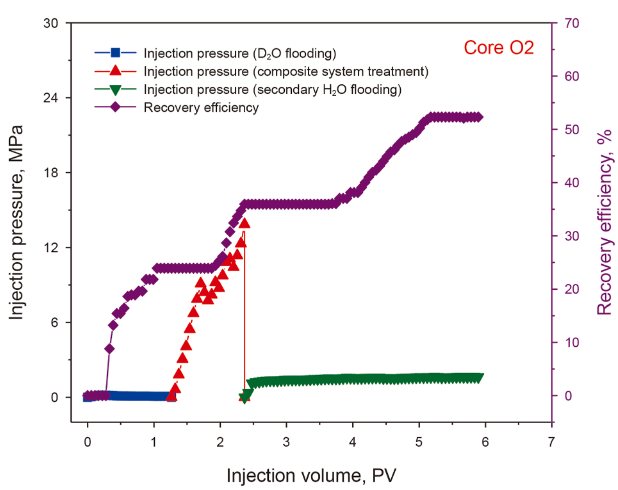


Fig. 9. Pressure dynamics during injection and plugging phases of the composite gel system in heterogeneous rock cores saturated with oil.

single ISCPG system after secondary heavy water flooding. The amplitude was lower in the lowly permeable formations. Additionally, the total NMR signal amplitude was less than that of the single ISCPG system. The results further confirmed that the composite gel system preferentially propagated through highly permeable zones, efficiently plugging dominant flow pathways. In other words, its penetration into moderately and lowly permeable zones remained restricted, minimizing formation impairment and eliminating the need for supplementary plugging treatments, thus mitigating reservoir damage. Furthermore, the core treated with the composite gel system retained less oil. It also demonstrated that the composite gel system provided better oil displacement efficiency than the single ISCPG system.

3.3.3. *Contribution analysis of oil recovery enhancement in different layers of oil-saturated core samples*

NMR technology was then used to study the conformance improvement effects and formation damage caused by single gel injection and the composite gel system in oil-saturated heterogeneous sandstone core samples. Figs. 13 and 14 show the NMR signal amplitudes of the single ISCPG injection and the composite gel system in different layers of oil-saturated core samples, respectively.

As shown in Fig. 13, after completing the three flooding stages (heavy water flooding, single ISCPG injection, and secondary heavy water flooding), the NMR signal amplitude in lowly permeable layers remained negative, whereas moderately-to-highly permeable layers and the entire core sample were positive. Additionally, the overall NMR signal amplitude of the core sample showed a

Table 2
Comparison of oil displacement performance for different gel systems.

Conformance improvement system	Experimental scheme	Water flooding recovery, %	Post-plugging recovery, %
Composite gel system	Injection of 0.2 PV BPPG + 0.8 PV ISCPG	23.91	52.34
Single ISCPG system	Injection of 1 PV ISCPG	23.45[a]	42.20[a]

[a] Data were sourced from the reference Zhu et al. (2025).

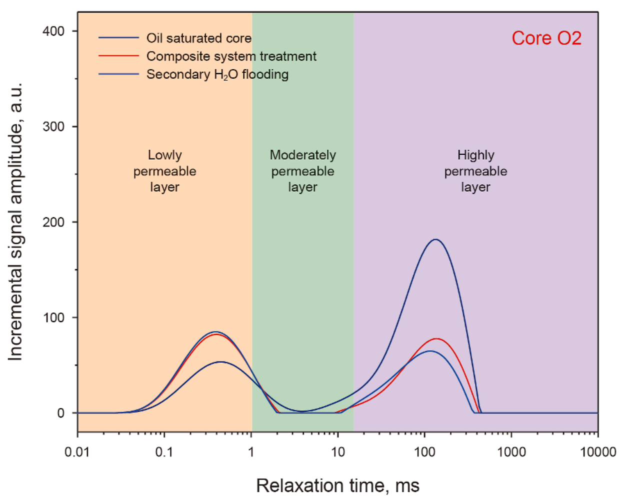


Fig. 10. Dynamic T_2 curves of composite gel system in heterogeneous core saturated with oil.

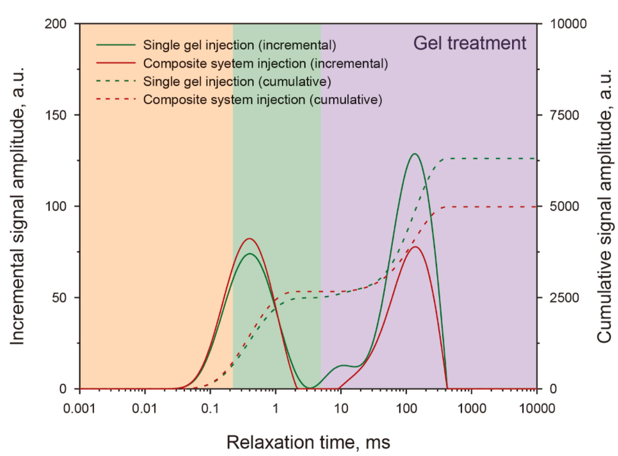


Fig. 11. Comparison of NMR T_2 spectra of different conformance improvement systems in oil-saturated core samples. Data for the single ISCPG injection was sourced from Zhu et al. (2025).

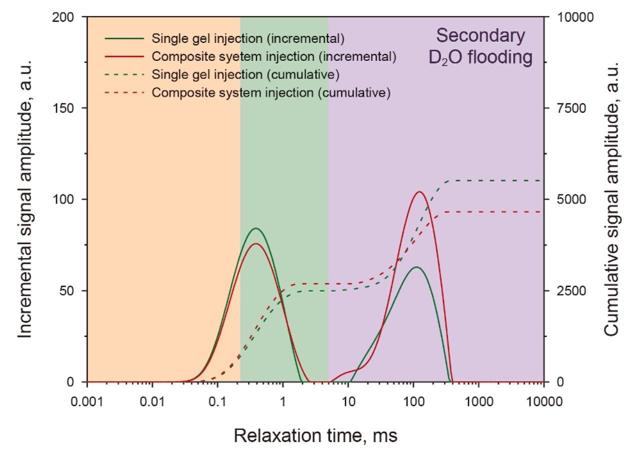


Fig. 12. Comparison of NMR T_2 spectra of different conformance improvement systems in water-saturated core samples after secondary heavy water flooding. Data for the single ISCPG injection was sourced from Zhu et al. (2025).

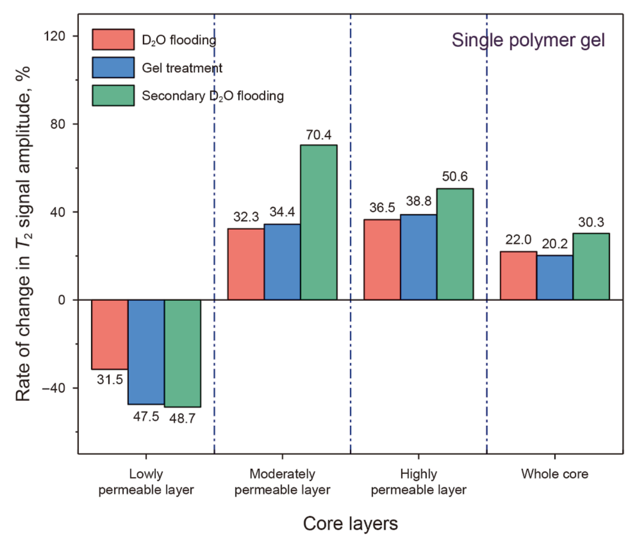


Fig. 13. Comparison of NMR signals across different layers in oil-saturated core samples treated by the single gel injection system. Data for the single ISCPG injection was sourced from Zhu et al. (2025).

positive response after all three flooding stages. It indicated that the single ISCPG system effectively improved conformance in both moderately-to-highly permeable layers and the complete core sample, thereby improving oil recovery efficiency. However, a certain level of formation damage was observed in lowly permeable layers.

Fig. 14 shows that the composite gel system also effectively improved conformance in moderately-to-highly permeable layers and the entire core, expanding sweep efficiency and enhancing oil displacement efficiency, though a certain level of formation damage was observed in lowly permeable formations.

In addition, a comparison between Figs. 13 and 14 reveals that the core samples treated with the composite gel system showed lower absolute values of NMR signal amplitude in lowly permeable layers and greater overall NMR signal amplitudes compared to those treated with the single gel system. It demonstrated that the composite gel system significantly mitigated damage to oil-bearing zones without necessitating additional plugging while effectively minimizing formation damage. Additionally, the composite system exhibits clear advantages in both sweep efficiency expansion and oil displacement efficiency enhancement.

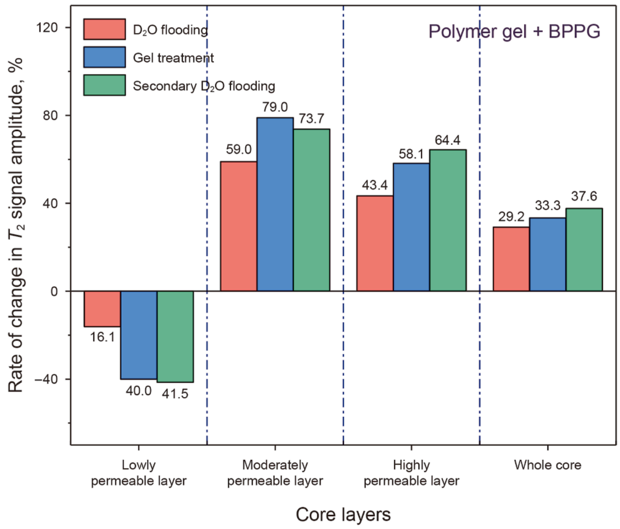


Fig. 14. Comparison of NMR signals across different layers in oil-saturated core samples treated by the composite gel system.

4. Conclusions

This study investigated the conformance improvement performance and oil recovery enhancement effects of a new injection method of the composite gel system (ISCPG-BPPG) and gel breaker in heterogeneous sandstone cores through core plugging experiments and NMR technology. A comparative analysis with single gel systems yielded the following conclusions:

(1) This paper proposed using BPPG as a pre-flush slug before ISCPG injection, followed by gel breaker treatment at the core face. This approach mitigated damage to lowly permeable zones while enhancing sweep efficiency and oil recovery.
(2) A gel breaker formulation containing depolymerizer (JJ-3) and ammonium persulfate in a 2:8 mass ratio (total concentration of 2%) demonstrated effective gel-breaking performance for the ISCPG-BPPG composite system.
(3) The composite gel system composed of ISCPG and BPPG effectively plugs core pores, diverting subsequent waterflood to lowly to moderately permeable zones after the gel-breaking process. It improved utilization of these zones, enhanced sweep efficiency, and demonstrated excellent plugging and conformance improvement performance.
(4) BPPG in the composite gel system prevented further ISCPG migration into non-target zones, reducing damage to lowly to moderately permeable zones and providing superior reservoir protection.
(5) The new injection method of the ISCPG-BPPG composite gel system and gel breaker showed remarkable oil displacement performance in oil-saturated heterogeneous cores. The single ISCPG system enhanced oil recovery by 18.75% OOIP, whereas the ISCPG-BPPG composite gel system attained a higher recovery degree of 28.43% OOIP, corresponding to a 9.68% OOIP improvement.
(6) The composite gel system significantly outperformed single gel systems in both conformance improvement and oil recovery enhancement after the gel-break process. The synergistic effect between ISCPG and BPPG optimized conformance improvement while minimizing damage to non-target zones, demonstrating clear advantages in reservoir protection.

CRediT authorship contribution statement

Jiong Zhang: Writing – original draft, Validation, Investigation, Data curation. **Hong-Gen Tan:** Validation, Investigation, Data curation. **Tao Zhang:** Validation, Investigation, Data curation. **Ying-Qi Gao:** Validation, Investigation, Data curation. **Hong-Bin Cheng:** Investigation, Data curation. **Hong-Yu Li:** Investigation, Data curation. **Dao-Yi Zhu:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Conceptualization.

Declaration of competing interests

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.

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