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Original Paper

Importance of conformance control in reinforcing synergy of CO_2 EOR and sequestration

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ABSTRACT

Injecting CO_2 into hydrocarbon reservoirs can enhance the recovery of hydrocarbon resources, and simultaneously, CO_2 can be stored in the reservoirs, reducing considerable amount of carbon emissions in the atmosphere. However, injected CO_2 tends to go through fractures, high-permeability channels and streaks present in reservoirs, resulting in inefficient hydrocarbon recovery coupled with low CO_2 storage performance. Conformance treatments with CO_2-resistant crosslinked polymer gels were performed in this study to mitigate the CO_2 channeling issue and promote the synergy between enhanced oil recovery (EOR) and subsurface sequestration of CO_2. Based on a typical low-permeability CO_2-flooding reservoir in China, studies were performed to investigate the EOR and CO_2 storage performance with and without conformance treatment. The effect of permeability contrast between the channels and reservoir matrices, treatment size, and plugging strength on the efficiency of oil recovery and CO_2 storage was systematically investigated. The results indicated that after conformance treatments, the CO_2 channeling problem was mitigated during CO_2 flooding and storage. The injected CO_2 was more effectively utilized to recover the hydrocarbons, and entered wider spectrum of pore spaces. Consequently, more CO_2 was trapped underground. Pronounced factors on the synergy of EOR and CO_2 storage were figured out. Compared with the treatment size, the CO_2 storage efficiency was more sensitive to the plugging strength of the conformance treatment materials. This observation was important for conformance treatment design in CCUS-EOR projects. According to this study, the materials should reduce the channel permeability to make the channel/matrix permeability ratio below 30. The results demonstrate the importance of conformance treatment in maximizing the performance of CCUS-EOR process to achieve both oil recovery improvement and efficient carbon storage. This study provides guidelines for successful field applications of CO_2 transport control in CO_2 geo-utilization and storage.
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1. Introduction

The global demand of oil and gas keeps increasing. At the same time, “carbon neutrality” strategy has been proposed to solve the global climate change problem. Carbon Capture, Utilization, and Storage (CCUS) is an indispensable way to achieve the “carbon neutrality” target. Injecting CO_2 into oil reservoirs can not only enhance oil recovery (termed as CCUS-EOR), but also realize geological storage of the CO_2, removing a large fraction of CO_2 emissions from the atmosphere. CCUS-EOR has been demonstrated

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an effective and economically feasible way to achieve large-scale CO_2 reduction. China intends to realize the goal of "carbon emission summit" in 2030 and "carbon neutrality" in 2060. To achieve these goals, China's overall emission reduction demand via CCUS in 2030 will be 2×10^7–4.08×10^8 t/a (Zhang et al., 2021). Meanwhile, the geological utilization and storage potential in China is very significant (1.5×10^{12}–3.0×10^{12} t CO_2 onshore), which can theoretically meet the demand for emission reduction. However, the current CO_2 geological utilization and storage capacity in China is only 1.21×10^6 t/a (Zhang et al., 2021), which is far below the demand for emission reduction. Therefore, enormous potential of geological utilization and storage has not been fully utilized.

Most reservoirs in CCUS-EOR projects in China are featured with low permeabilities (< 50 md) (Qin et al., 2015; Hu et al., 2019). Specifically, 10–50 md is ordinary low permeability, 1–10 md is extra-low permeability, and 0.1–1 md is ultra-low permeability. China is rich in low permeability oil and gas resources, accounting for about 46% of the total reserves of the country. In recent years, low permeability oil reservoirs account for more than 70% of the newly proved reserves (Li, 2020). Injecting CO_2 is an effective way to unlock the low-permeability resources (Huang et al., 2022; Li, 2020; Zhang et al., 2018, 2019). Recently, Liu and Rui (2022a, b) proposed a new concept, named storage-driven CO_2-EOR, which collaborates CO_2-EOR with carbon storage in oil reservoirs to achieve optimal oil recovery and carbon storage simultaneously. It provides a feasible approach to a paradigm shift in hydrocarbon recovery, from a massive-emission process to a net-zero-emission one.

However, fractures and high-permeability channels are usually present in the reservoirs, especially at scales in consideration. Being exposed to such heterogeneities, injected CO_2 tends to channel from injection wells to production wells through the high-permeability streaks and escapes to the surface prematurely, failing to achieve effective geo-storage, with effective storage rates less than 20% (Ye et al., 2021). Seriousness of such gas channeling issues was an important reason to restrain the expansion of CO_2-EOR pilot tests to large scale applications in the 1990s in China (Li, 2020). The channeling problem has not been effectively solved although important theoretical and technical progresses have been made over the years.

Since the commercial applications of CO_2 flooding in the 1970s, a variety of strategies have been developed to control CO_2 channeling, such as water-alternating-gas injection (WAG), mechanical isolation, cement squeeze, gel, foam, and CO_2 thickening (Enick et al., 2012; Qin et al., 2015). The WAG method has been widely used, but it has poor gas-channeling-control ability when the heterogeneity issue is too severe (such as the existence of macroscopic fractures) (Enick et al., 2012; Sun et al., 2020). Polymer gels can seal off the high-permeability features, improve crossflow and effectively inhibit channeling of displacing fluids, which have been widely used in water flooding and chemical flooding (Bai et al., 2013; Seright and Brattekas, 2021; Kang et al., 2021; Zhu et al., 2017; Sun et al., 2020). Polymer gels are expected to selectively block the flow of CO_2, forcing subsequent injected CO_2 fluid to enter the low-permeability zones where the oil saturation is high. As a result, more oil can be recovered and due to the improvement of volumetric coverage, CO_2 can enter into more pore spaces. Therefore, it cannot only improve oil recovery, but also force the CO_2 to enter additional pore spaces and be trapped, improving the CO_2 storage efficiency.

Different gel systems have been developed for conformance control. In-situ polymerization gel systems were applied in early field tests in 1980s (Woods et al., 1986; Martin and Kovarik, 1987). For such gel systems, monomer solutions with crosslinkers were injected into the reservoirs to be treated. *In-situ* polymerization and crosslinking reactions took place underground to form gels. The gelant was easy to be injected due to the low viscosity, which was close to water. However, the polymerization and gelation reactions were susceptible to formation conditions such as temperature, brine salinity and composition, pH, and shearing. Also, these gel systems could enter and damage the low-permeability zones where remaining oil was present (Seright, 1995, 1997; Seright and Lee, 1999). Another way is to inject polymer solutions containing cross-linking agents (e.g., Cr^{3+}). The gelant viscosities are higher, close to polymer solutions. Higher viscosities alleviate the formation damage problem and the shortcomings associated with in-situ polymerization (Seright, 1997; Sydansk and Romero-Zeron, 2011).

In 1990s, Seright studied the conformance improvement performance by injecting preformed bulk gels (PBG) into heterogeneous reservoirs (Seright, 1997). Crosslinking reactions take place and gels are formed before they are injected into reservoirs. The PBG systems overcome some drawbacks associated with in-situ gels. PBGs are proven to be effective to solve fracture-type features in reservoirs (Seright, 1997, 1999a, b, 2001, 2003; Raje et al., 1999; Asghari et al., 1999; Fakher et al., 2018). PBGs have been used in CO_2-flooding projects in the United States (Hild and Wackowski, 1998) and the Middle East (Karaoguz et al., 2004). However, PBGs are difficult to achieve in-depth profile control due to poor injectivity in smaller fractures or matrix-type channels. Experiments showed that the required injection pressure gradient would exceed 200 psi/ft even when the permeability of matrix type channels was up to 27 darcies (Seright, 1999a). Such a high-pressure gradient is only found within a few feet around a wellbore. In the late 1990s, millimeter-sized preformed gel particles (PPG) were developed for in-depth conformance control. PPGs were successfully applied in Zhongyuan Oilfield and were rapidly promoted thousands of wells (Coste et al., 2000; Bai et al., 2008, 2015). PPGs effectively overcome some drawbacks of in-situ gels and PBGs (Bai et al., 2015; Dai et al., 2017; Kang et al., 2021).

Since CO_2 is acidic and corrosive, different polymer gel systems have been developed to improve their CO_2-resistance capacity (Sun et al., 2020; Kang et al., 2021; Li et al., 2016). Lashari et al. (2019) studied macroscopic and microscopic rheological properties of composite gels used for CO_2 flooding conformance control. The addition of SiO_2 enhanced the water-holding capacity of the gels. Thereby, reducing the severity of dehydration of the gels under exposure to CO_2. Fakher et al. (2018) evaluated the plugging performance of HPAM gel under supercritical-CO_2 conditions, and found that the plugging ability of HPAM gel was insufficient when they were exposure to supercritical CO_2, especially under low-salinity conditions. Geng et al. (2019) and Ding et al. (2020) developed a pH-responsive nano/submicron-PPG copolymerized with PAM-AA. The effects of monomer type, crosslinker concentration and pH value on the physicochemical properties of gel particles were investigated. The physicochemical properties include morphology, Zeta potential and hydrodynamic diameter, and the mechanism of pH response of the gels. Pickering emulsions with additions of the nano/submicron-PPGs were found to be stable under low pH (acidic) conditions. Zhao et al. (2021), and Zhao and Bai (2022a, b, c) evaluated the selective plugging mechanism of micrometer-sized gel particles in heterogeneous reservoirs with super-permeable channels. Kang et al. (2021), Sun et al. (2020) and Zhu et al. (2017) summarized gel systems for conformance control.

However, unlike traditional CO_2-EOR projects, which are driven by the single goal of enhanced hydrocarbon resource recovery, CCUS-EOR projects are driven by multiple goals: enhanced hydrocarbon resource recovery, and optimal CO_2 geo-storage at the exit. Therefore, the requirements for conformance control in traditional CO_2-EOR projects and CCUS-EOR projects are also different. With an increasing emphasis on CO_2 reduction especially in recent years, more attention should be paid to the synergy of CO_2 EOR and sequestration. Conformance control of CO_2 flow in reservoirs is crucial to achieve the synergistic performance. Such studies are still highly scarce. This work intended to study the effect of conformance control in reinforcing the synergy with oil recovery and CO_2 storage. The impact of conformance channel permeability, treatment size, and plugging strength was systematically studied. Favorable conditions for reinforcing the synergy of CO_2 EOR and sequestration in low-permeability fractured reservoirs were discussed.

2. Methodology

A conceptual one-layer reservoir model with sealed boundaries was established based on published data of a CO_2-flood reservoir in H-95 block in Jilin Oilfield (Wang, 2013; Ren et al., 2011; Zhang et al., 2016). Particularly, Wang (2013) carried out systematic tests of the fluid properties and CO_2-oil interaction of this block. The published test results provide basis for this numerical simulation study. The model grids were 104 × 104 × 1 with a grid size of 3 m × 3 m × 10 m. The shape of all the grids is uniform. The reservoir dimension was 312 m × 312 m × 10 m. Corner-point grid system was used in the reservoir model. The grid sizes in the x and y directions were small enough to represent the channels and matrices of the reservoir. The grid size in the z direction was a little bit large (10 m) and there was only one layer in the model. This was in accordance with the assumption of "no gravitational override" of the injected CO_2. Meanwhile, coarsening grids appropriately can shorten the operation time to some extent, so the calculation efficiency could be improved.

The reservoir was developed by two parallel horizontal wells with an in-between well distance of 300 m. The horizontal length of the wells was 300 m. The reservoir matrix permeability was 3 md. The horizontal laterals of the wells lay in the middle of layer. The two horizontal wells located near the closed boundary to guarantee the direction of CO_2 was from the injection well to production well and fully utilized the driving energy of CO_2. Horizontal wells were adopted to take advantage of their advantages. As the reservoir model was consisted with a thin layer, vertical wells were not efficient to extract the hydrocarbon resources. By contrast, horizontal wells had a much larger contact area with the reservoir to develop the crude oil and inject and sequestrate CO_2 more efficiently. Also, the choice was in accordance with field practice as horizontal wells were used widely in extra-low permeability reservoirs to enhance the injectivity and productivity and ensure an economic injection rate and oil production rate.

High-permeability streaks and fractures were present in the reservoir. Three high-permeability channels with a width of 9 m were introduced to represent the streaks and fractures. The channels connected the injector and producer. The permeability of the channels depends on the cases to be researched. The reservoir model is shown in Fig. 1. The oil composition is summarized in Table 1. The basic data of fluids and reservoir was shown in Table 2. Table 3 and Table 4 present the PVT properties of the crude oil-CO_2 systems. The initial oil saturation was 0.56. Relative permeabilities of oil, water and CO_2 were shown in Fig. 2. The dataset of relative permeability is gained by a series of core experiments and normalized by Eclipse-SCAL software (Wang, 2013). Gel treatment was performed to seal off the channels. The channel permeability in each case study was specified in Table 5. The impact of treatment size, channel permeability, plugging strength on oil recovery and CO_2 storage performance was investigated through a series of case studies. The following assumptions were introduced in the simulation studies.

(1) The matrix of the reservoir was homogenous and isotropic;
(2) The temperature of the reservoir was uniform in each grid and kept constant during production. The flowing of fluid in the reservoir was assumed to be isothermal;
(3) The migration of CO_2 in the reservoir due to the buoyant force was ignored. That is, it was assumed there was no override of the injected CO_2. The fluid saturation distribution in the vertical direction was the same. This assumption was reasonable considering the small thickness of the reservoir.
(4) The two horizontal wells were located near the closed boundaries to guarantee the direction of CO_2 is from injection well to production well and fully utilize the driving energy of CO_2;
(5) The gel materials were assumed ideally placed in the pre-calculated position of the high-permeability channels without entering other position in the reservoir;
(6) Ignore the reaction of CO_2 with matrix or gel materials.

It should be noted that transport and placement of gel materials in fractures and matrix-type high-permeability channels are complex processes. Physical processes that are involved in are dehydration, leak-off, particle breakage, rheological behavior, disproportionate permeability reduction, inaccessible pore volume, CO_2-response behavior and etc. Detailed discussions on some of these topics can be found in the literature (Bai et al., 2013; Zhao et al., 2021; Zhao and Bai, 2022a, b, c; Seright, 1997, Seright and Brattekas, 2021; Willhite et al., 2002; Zhang and Bai, 2011; Imqam et al., 2017; Leng et al., 2021; Dai et al., 2017; Song et al., 2018; Sun and Bai, 2017; Sun et al., 2020, 2021; Wang and Bai, 2018). To make our study focused without going into the theoretical detail of the complex transport and placement processes of gel materials that are already covered in the already cited literature, we substantially simplified and scaled the treatment processes in the numerical studies. The gel materials selectively placed in the high-permeability channels without entering the reservoir matrices. The plugging ability of the materials could be maintained over the lifespan of reservoir development. In reality, the plugging ability tended to gradually diminish as more displacing fluid was injected and flowed through the reservoir. However, it could be remedied by being re-treated with gel materials. Also, the permeability reduction capacity was assumed the same to different fluids. Without getting into more complex treatment processes, we put our focus on the key questions of 1) what a conformance treatment is required in order to achieve synergy of CO_2 EOR and geo-sequestration, and 2) key parameters and favorable conditions for conformance treatment to reinforce the synergistic outcomes.

3. Results and discussion

Fifteen sets of numerical simulations were performed to investigate the effect of permeability contrast (K_c/K_m), relative treatment size (L_t/L_c), and plugging strength (K_c/K_c') on oil recovery performance and CO_2 storage efficiency. The results are discussed in subsequent sections.

3.1. Effect of conformance control on EOR and CO_2-storage

In the base case (case 0), CO_2 flooding was performed without gel treatments. the CO_2 broke through after 160 days and a significant portion of oil was bypassed (see Fig. 3). Also, lower CO_2 saturation was observed in the bypassed areas. To improve the oil recovery and CO_2 storage, in case 1, gel treatment was performed to seal off the channels. Half length of the channels was sealed off by CO_2-resistant polymer gels (relative treatment size = L_t/L_c = 1/2). The channel permeabilities were reduced by a factor of 100

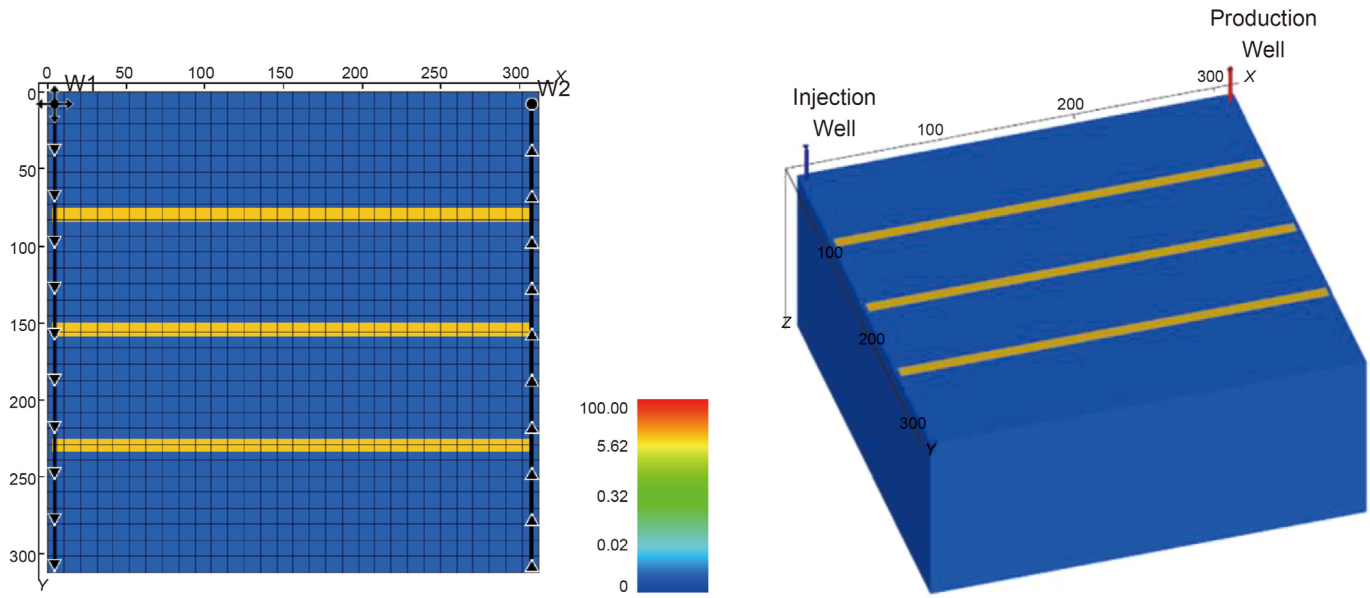


Fig. 1. 2D and 3D view of reservoir model (permeability in darcy).

Table 1
Oil composition (Wang, 2013; Ren et al., 2011; Zhang et al., 2016).

Components	Fraction, mol%	Fraction, wt%
CO_2	0.1	0.02
N_2	2.62	0.42
C_1	16.46	1.51
C_2	4.29	0.74
C_3	3.24	0.82
iC_4	0.49	0.16
nC_4	1.92	0.64
iC_5	0.69	0.29
nC_5	1.88	0.78
C_6	2.99	1.44
C_{7+}	65.32	93.18
Total	100	100

Note: Relative density and MW of C_{7+} was 0.8437 and 230 respectively.

(plugging strength, quantified with Residual Resistance Factor, $RRF = 100$). For comparison, another case study was performed in which no gel treatment was performed (case 0). Detailed information of the model variants was summarized in Table 5 along with Table 2 for basic data. The oil recovery performance and CO_2 storage efficiency with and without gel treatment were shown in Figs. 3–5.

As expected, the CO_2 broke through the reservoir quickly when high-permeability channels were present in the reservoir. The CO_2 breakthrough was delayed after gel treatment from 160 days to 220 days (Fig. 4). As seen in Fig. 3c and g, the remaining oil saturation was located between the channels. The swept area was obviously increased after conformance treatment. The area with high remaining oil saturation was decreased. The injected CO_2 was diverted to the remaining oil region to displace the bypassed oil due

Table 2
Basic parameters (Wang, 2013; Ren et al., 2011; Zhang et al., 2016).

Parameter	Value
Grid dimension	104 × 104 × 1
Grid size	3 × 3 × 10 m^3
Reservoir dimension	312 × 312 × 10 m^3
Porosity	0.1
Initial oil saturation (S_{oi})	0.56
Residual oil saturation (S_{or})	0.25
Depth	2160 m
Thickness	10 m
Minimum miscibility pressure (MMP)	22 MPa
Reservoir temperature	95 °C
Reservoir pressure	21 MPa
Permeability of matrix (K_m)	3 md
Permeability of channels (K_c)	10 darcies
No. of channels	3
Bubble point	7.83 MPa
Live oil density	0.7861 g/cm^3
Dead oil density	0.8437 g/cm^3
Oil viscosity	1.79 mPa s
Single-stage flash gas-oil ratio (standard conditions), m^3/m^3	34
Original volume factor	1.1222
Molecular weight of degassed oil	230
Oil Shrinkage factor (standard conditions)	11.42
Thermal expansion coefficient	1.0509×10^{-4} K^{-1}

Table 3
Constant composition expansion experiment data at 95 °C (Wang, 2013; Ren et al., 2011; Zhang et al., 2016).

Pressure, MPa	Relative volume	Volume factor	Density, g/cm^3	Viscosity, mPa·s
22.5	0.9785	1.1222	0.7861	1.7904
20	0.9816	1.1258	0.7836	1.7400
16	0.9870	1.1319	0.7794	1.6885
12	0.9930	1.1388	0.7747	1.6036
8	0.9997	1.1465	0.7694	1.5154
7.83	1.0000	1.1469	0.7692	1.4237
4	1.3343	1.1143	0.7803	1.4198
1	4.0212	1.0780	0.7944	1.4915
0.5	8.1654	1.0694	0.7991	1.5521
0.1	49.4073	1.0406	0.8093	1.5617

Table 4
Swelling test data for the CO_2-Oil System at 95 °C (Wang, 2013; Ren et al., 2011; Zhang et al., 2016).

Ratio of injected gas, %	Saturated pressure, MPa	Swelling factor	Volume factor	Ratio of dissolved gas and oil, m^3/m^3	Viscosity of oil, mPa·s	Solubility of CO_2, m^3/m^3	Density of oil, kg/m^3
0	7.83	1	1.1222	32.38	1.42	0	769.22
10	9.43	1.028	1.1540	46.80	1.39	14.42	769.14
20	11.27	1.064	1.1937	64.67	1.33	32.29	769.08
30	13.48	1.109	1.2444	87.54	1.22	55.16	769.21
40	16.31	1.168	1.3110	117.96	1.09	85.58	769.98
50	20.46	1.248	1.4003	160.54	0.95	128.16	773.11
60	28.46	1.352	1.5177	224.54	0.84	192.16	785.57

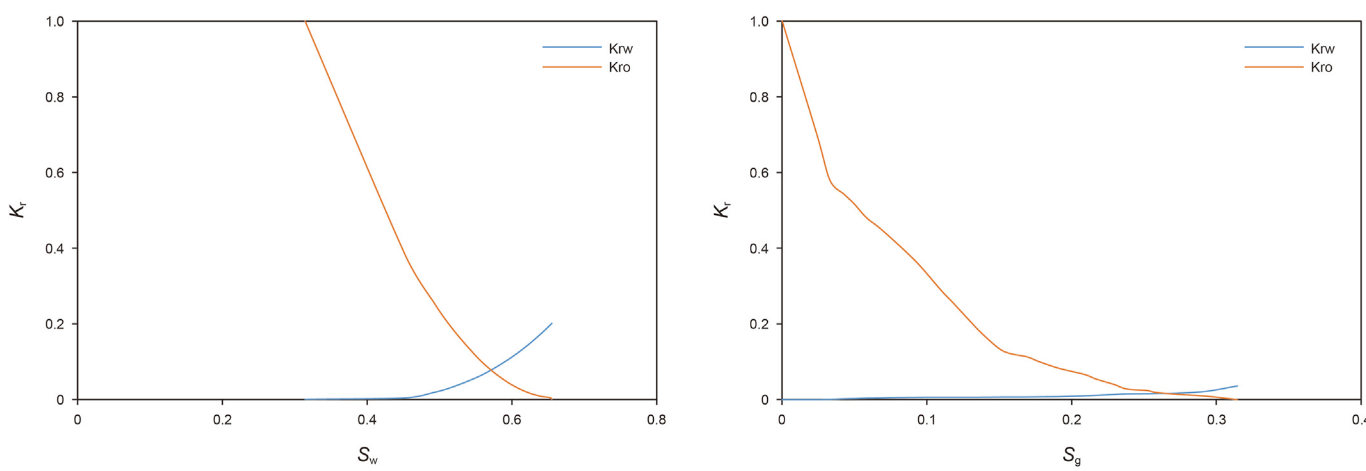


Fig. 2. Relative permeabilities of oil, water and gas (Wang, 2013; Ren et al., 2011; Zhang et al., 2016).

to reservoir heterogeneity. Meanwhile, the CO_2 was trapped in this area, as indicated by high CO_2 saturations shown in Fig. 3d and h. This trapped CO_2 means the CO_2 left in the system and therefore sequestered unless an attempt to be made for its recovery for re-use. After conformance treatments, 6.5% OOIP (0.036 PV) more oil was recovered in 25 years (5.00 PV of CO_2 was injected), and in the first 10 years (1.55 PV CO_2 injection), the oil incremental was 4.8% OOIP (0.027 PV). After breakthrough at the producer, the overall CO_2 storage efficiency kept decreasing. However, the GOR behavior was also improved after conformance treatment. As shown in Fig. 6, GOR increase rate was significantly mitigated with conformance treatment. Accordingly, the dynamic CO_2 storage efficiency, E_s(daily), was increased and resulted in a higher overall CO_2 storage efficiency, E_s(cumulative). After 10 years, the E_s(cumulative) with conformance treatment was 35%, while it was 25% without conformance treatment. Therefore, more CO_2 was left behind in the reservoir.

The results demonstrated that the sweep efficiency was poor and CO_2 broke through easily when high-permeability channels were present in the reservoir. The storage capacity of the reservoir was not effectively utilized as a significant fraction of the pore spaces were occupied with high-saturation remaining oil. With conformance treatment, the channel permeability was reduced. CO_2 was diverted to the matrix to displace remaining oil. More CO_2 was trapped and stored in the pore spaces and therefore a higher storage efficiency was achieved. The results demonstrated the importance of conformance treatment on oil recovery and resulting CO_2 storage.

3.2. Effect of channel permeability (permeability contrast)

The effect of channel permeability (and permeability ratio, KR) on the performance of conformance treatment is studied. The channel permeability along with KR represent the severity of heterogeneity of the reservoir. In this study, the heterogeneity was adjusted by changing the channel permeability. The channel

Table 5
Information of case studies.

Factors	Simulations
Without treatment	Case 0 (base case):
	K_m: 3 md
	K_c: 10 darcies
	No. of channels: 3
	Gel treatment: not performed
Permeability ratio (Channel Permeability K_c)	Treatment size: 1/2 L_c
	Plugging strength: $RRF = 100$ ($K_c' = 1/100$ of K_c)
	Case 1: $K_c = 10$ darcies
	Case 2: $K_c = 100$ darcies
	Case 3: $K_c = 1$ darcies
	Case 4: $K_c = 0.1$ darcies
Treatment size (L_t)	K_c: 10 darcies;
	Plugging strength: $RRF = 100$ ($K_c' = 1/100$ of K_c)
	Case 5: $L_t = 1/100\ L_c$
	Case 6: $L_t = 1/30\ L_c$
	Case 7: $L_t = 1/5\ L_c$
	Case 8: $L_t = 2/3\ L_c$
	Case 9: $L_t = 1/1\ L_c$
Plugging strength ($RRF = K_c/K_c$')	K_c: 10 darcies; Treatment size: $L_t = 1/2$ of L_c
	Case 10: $RRF = 3$
	Case 11: $RRF = 10$
	Case 12: $RRF = 30$
	Case 13: $RRF = 500$
	Case 14: $RRF = 10000$ (i.e., $K_c' = 1$ md)

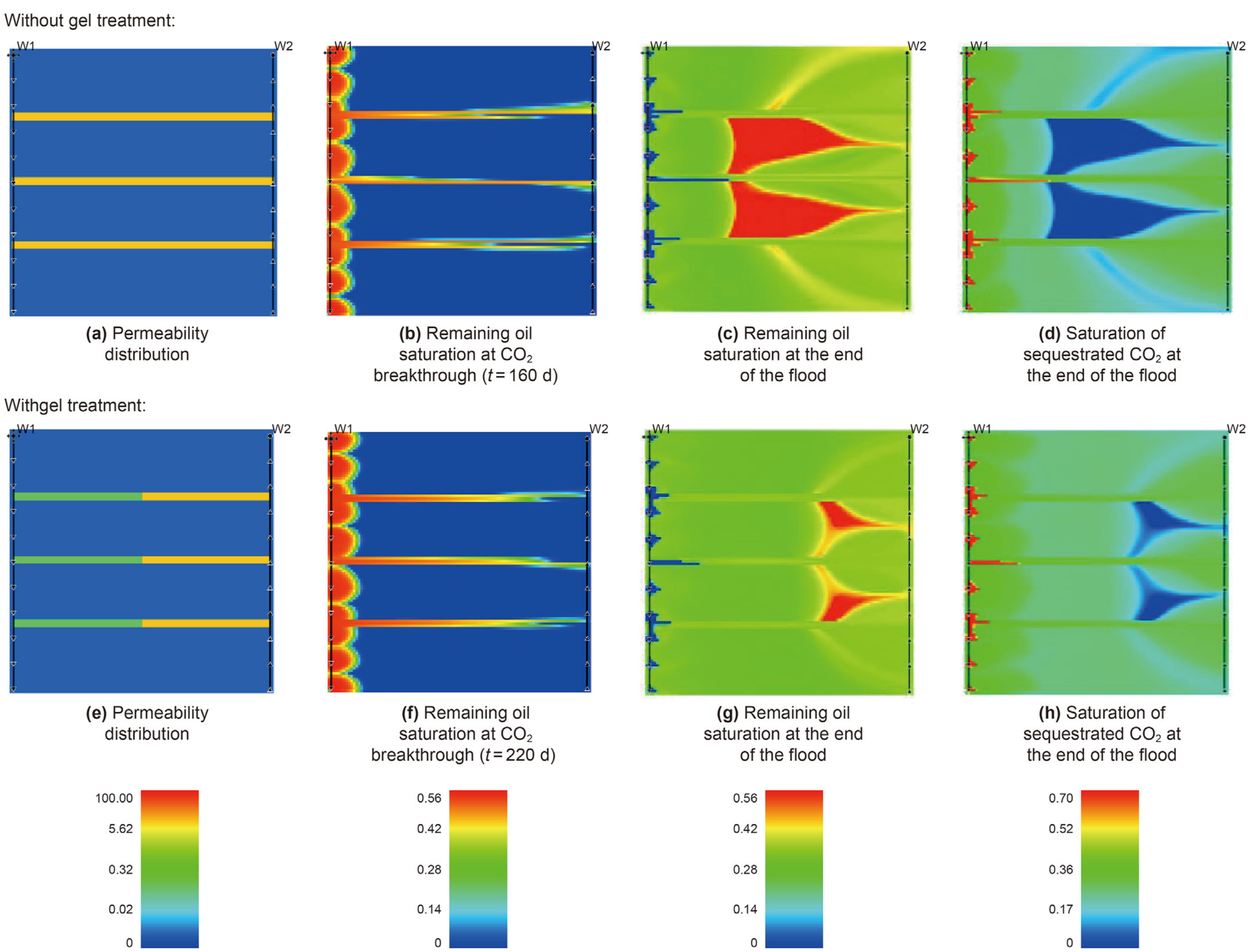


Fig. 3. Results of base case studies with and without gel treatment (color scales are also applied to subsequent cloud plots).

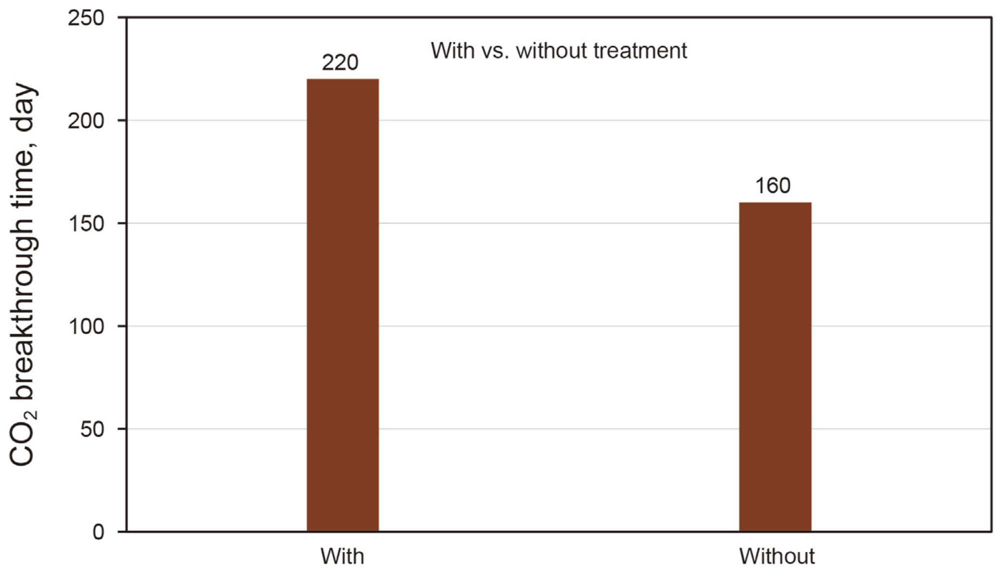


Fig. 4. Comparison of CO_2 breakthrough times with and without gel treatment.

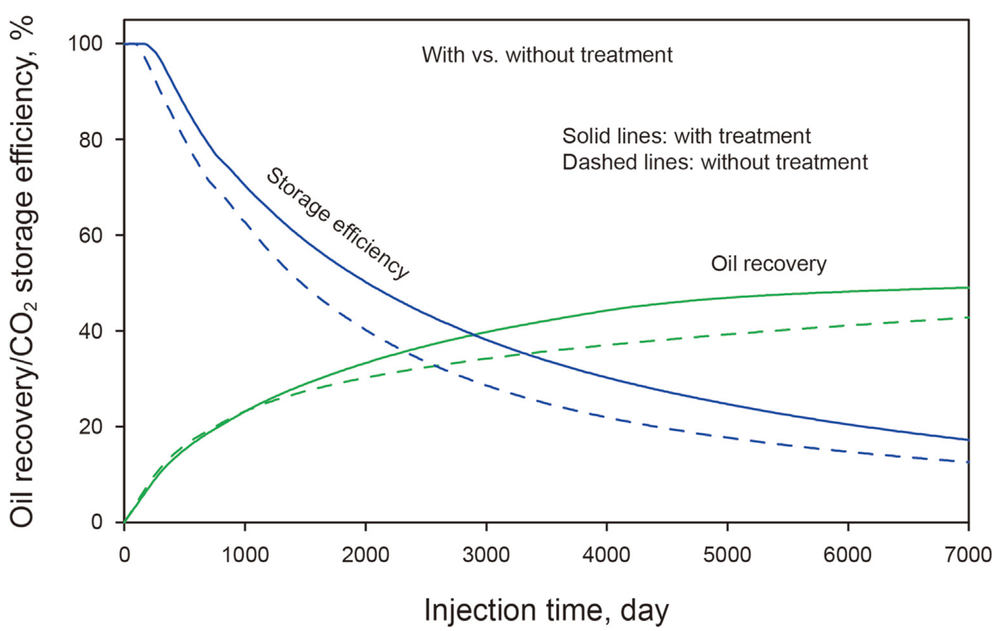


Fig. 5. Comparison of oil recovery performance and CO_2 storage efficiency with and without gel treatment.

permeability was set at 0.1, 1, 10, and 100 darcies, respectively. The results were summarized in Figs. 7–12.

CO_2 breakthrough occurred earlier as the channel permeability increased (Fig. 7). The breakthrough time was 1320 days when the channel permeability was 0.1 darcies (initial KR = 100:3), and decreased to 620 days when the channel permeability reduced to 1 darcies (KR = 1000:3), and 220 days and 180 days when KR = 10,000:3 and 100,000:3, respectively. Note that after gel treatment, the channel permeability and KR were reduced by a factor of 1000:3. After gas breakthrough, producing GOR increased faster, indicating a more severe channeling problem as the reservoir become more heterogeneous. A closer look at the results (Fig. 7) indicated that as $K_c/K_m < 10$, the existence of high-k streaks had a negligible impact on the breakthrough time. This behavior could be explained with the concept of flow capacity. Due to the small cross-sectional area of the channel systems compared with the entire reservoir, the flow capacity (K_cA_c) and the effect of fractures on the channeling problem are limited. The effect of channels become pronounced when K_c/K_m increased over 1000:3. The impact of channels on breakthrough time levelled off when the KR was too large ($K_c > 10$ darcies, and KR > 10000:3). The less sensitive trend was due to the extremely severe heterogeneity (super-high channel permeability) (Figs. 8 and 9). The oil recovery improvement was more significant when the KR was increased (Fig. 10). That is, the conformance treatment had a better chance to improve the oil recovery performance when the heterogeneity problem was more serious. The KR also impacted the GOR behavior (Fig. 11). After CO_2 breakthrough, the GOR increases more quickly as KR was larger. The increase trend is similar and the impact of KR become less significant when KR < 1000:3. This effect was more clearly

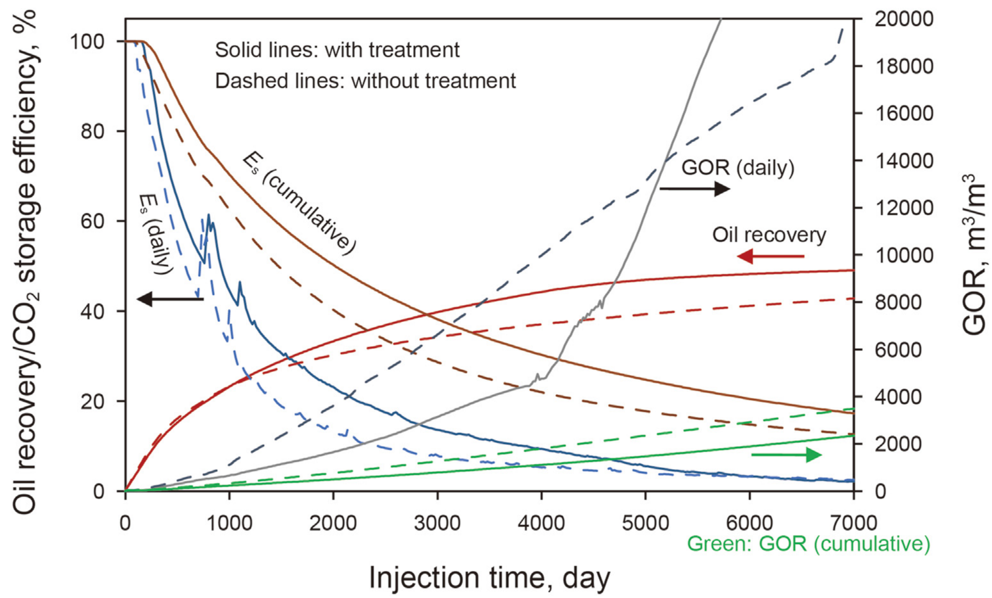


Fig. 6. Comparison of oil recovery performance and CO_2 storage efficiency with and without gel treatment.

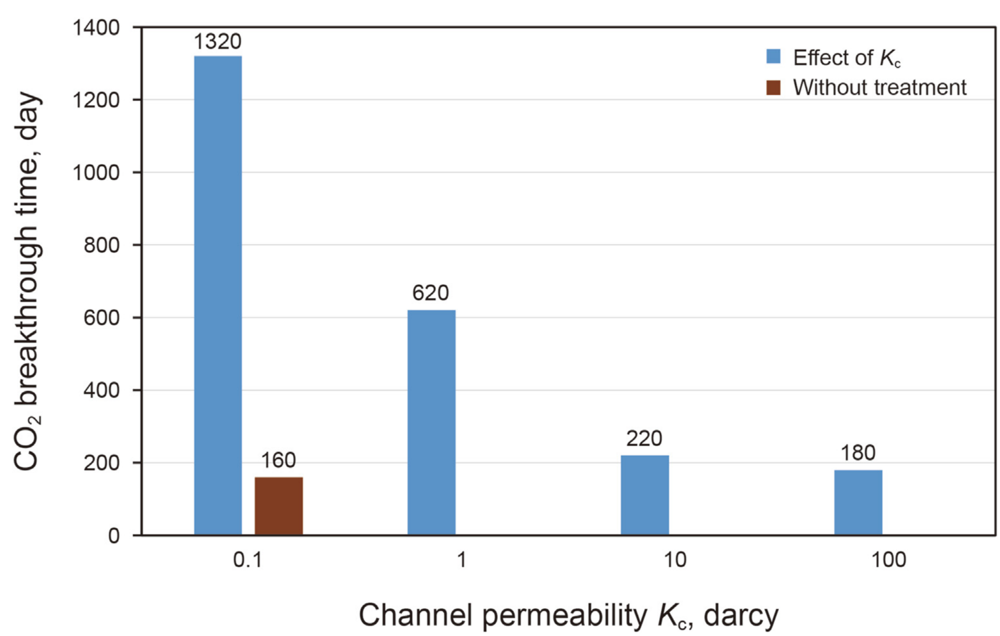


Fig. 7. Breakthrough times of injected CO_2.

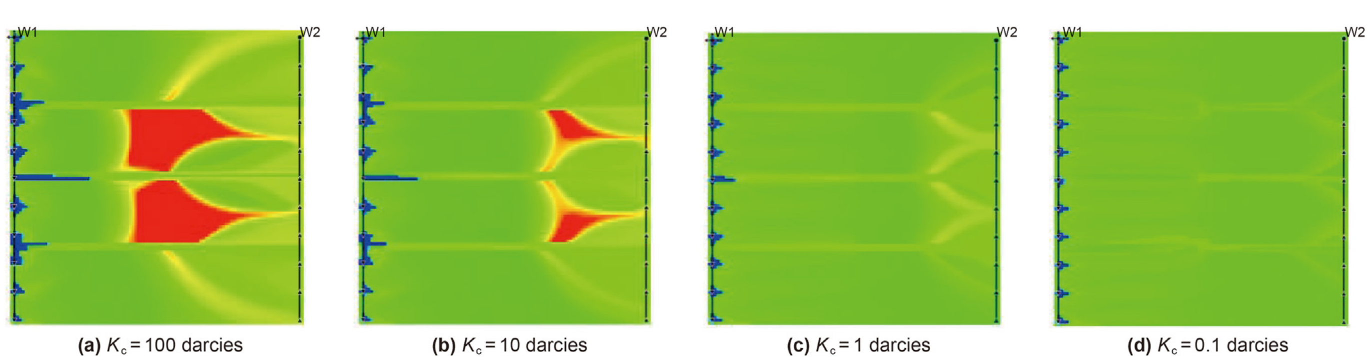
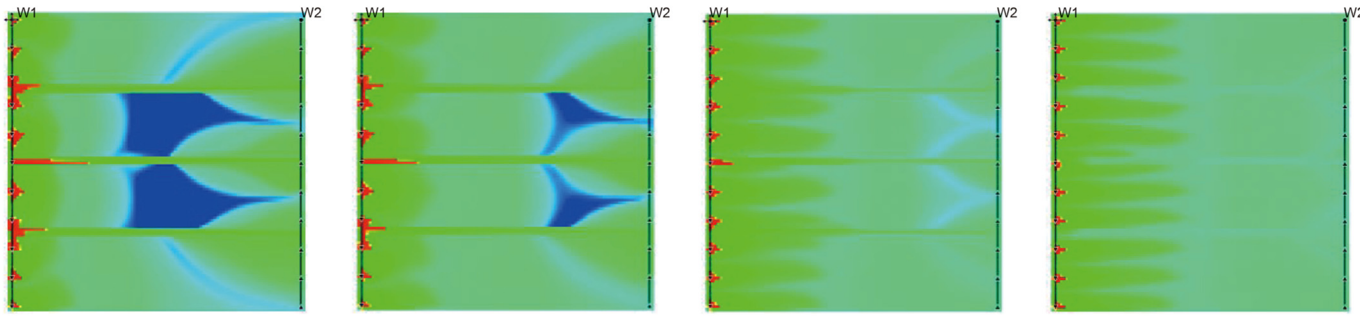


Fig. 8. Effect of channel permeability (K_c) on remaining oil saturation distribution.



(a) K_c = 100 darcies **(b)** K_c = 10 darcies **(c)** K_c = 1 darcies **(d)** K_c = 0.1 darcies

Fig. 9. Effect of channel permeability (K_c) on saturation distribution of sequestrated CO_2.

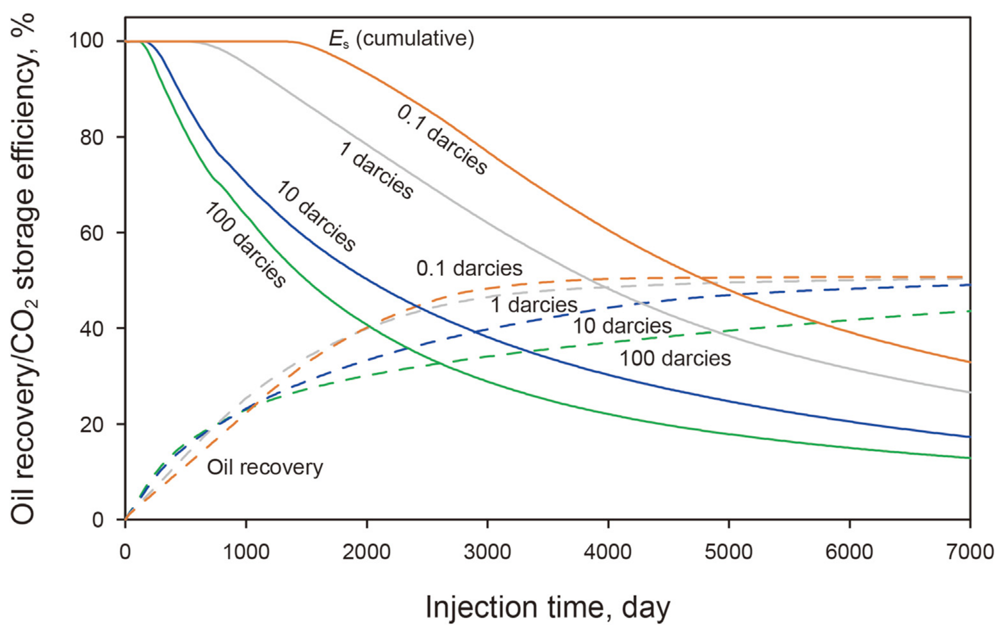


Fig. 10. Effect of channel permeability (K_c) on oil recovery and CO_2 storage.

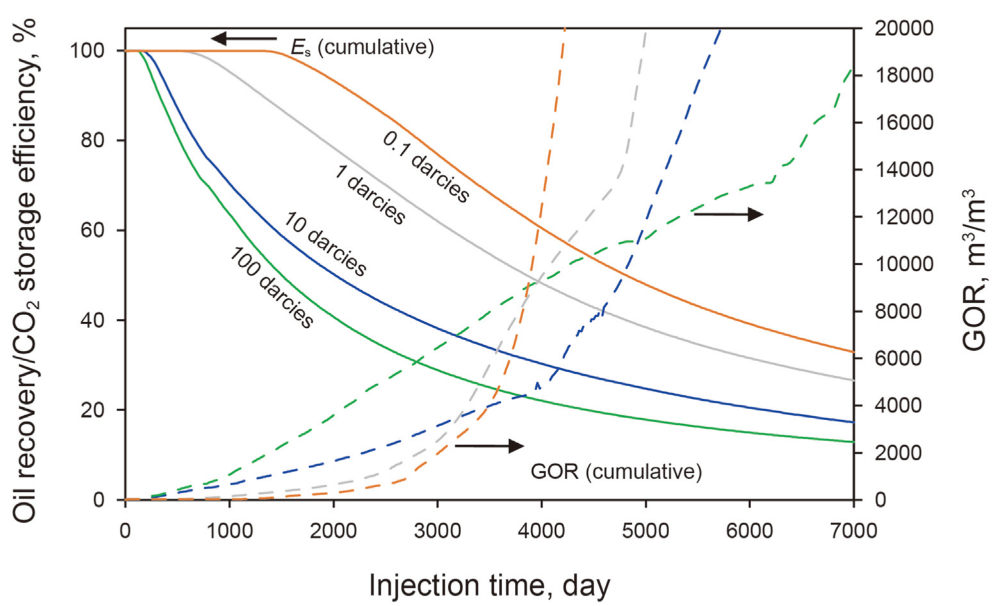


Fig. 11. Effect of channel permeability (K_c) on daily GOR and CO_2 storage.

demonstrated in Fig. 12.

More importantly, compared with the oil recovery performance, the CO_2 storage efficiency was more sensitive to KR (Fig. 10). This behavior has crucial implications on the application of CO_2-EOR, as carbon sequestration plays a more important role according to the zero-emission target. The storage efficiency reduced more rapidly as the channels were more permeable. A higher CO_2 storage efficiency could be achieved when the reservoir was more homogeneous. Conformance treatment was necessary to suppress the channeling of CO_2 through the high-k streaks. After the channels were sealed off, the injected CO_2 was forced into the matrices of the reservoir to displace the remaining oil. Meanwhile, more CO_2 was trapped in the pore spaces of the matrices. Therefore, the storage capacity and efficiency were increased.

3.3. Effect of treatment size

The effect of treatment size on oil recovery and CO_2 storage was also studied. Treatment size was quantified with the relative distance of the channel treated against the total channel length. The treatment size was set at 1/100 L_c, 1/30 L_c, 1/5 L_c, 1/2 L_c, 2/3 L_c, and L_c. The results were summarized in Figs. 13–18. Unswept area of the reservoir slightly decreased when the treatment size was increased from 1/100 L_c to 1/5 L_c, as indicated by the red area in Fig. 13. The unswept area was obviously diminished when the treatment size was increased to 1/2 L_c. Meanwhile, the CO_2 breakthrough was delayed, from 160 days to 220 days with a treatment size of 1/2 L_c (see Fig. 14). The sweep efficiency of the injected CO_2 was increased, and a higher oil recovery was achieved, leading to higher CO_2 occupancy of the pore space. Accordingly, as seen in Fig. 15, the CO_2 saturation was increased, resulting in higher CO_2 storage efficiency, as proven in Figs. 16 and 17. Compared with the permeability contrast, the impact of treatment size on CO_2 breakthrough time was mild. However, the treatment size had a significant impact on the GOR behavior and CO_2 storage efficiency. As shown in Fig. 18, the GOR increased much more rapidly when the treatment size was insufficient, and accordingly, storage efficiency of CO_2 was decreased. The reason was that the gel bank was not large enough to resist the CO_2 flow in high-permeability areas. Thus, the subsequently injected CO_2 could flow back into the channels and circulate to the producer instead of displacing the remaining oil (see Fig. 14). Therefore, to achieve a satisfactory CO_2 storage efficiency, treatment size should be large enough, at least 1/2 L_c in this study. The results demonstrated the importance of in-depth conformance control for effective CO_2 geological storage, while short-distance near-wellbore treatment was insufficient to mitigate CO_2 channeling. Nano-/micrometer-sized particle gels have the ability to propagate deep into reservoirs to achieve in-depth conformance control. In field practice, inter-well chemical tracer tests were often performed to assist in evaluating the channel size.

3.4. Effect of plugging strength

The effect of plugging strength of the conformance treatment materials on CO_2 channeling, oil recovery, and carbon dioxide storage was studied. Plugging strength was quantified with the residual resistance factor (RRF). The RRF was set at 3, 10, 30, 100, 500, and 10,000. The other parameters were kept the same. The results were summarized in Figs. 19–24.

As shown in Fig. 19, breakthrough times were close to each other when RRF was below 100. The delay in breakthrough was small, from 180 days to 220 days. Note that at the beginning, the initial KR was 10,000:3. The KR was reduced to 10 when RRF = 100. The results suggested that in order to effectively suppress the channeling issue, the gels should plug the channels and reduce the KR to the level of less than 100:3. The breakthrough time was delayed to 440 days and 1040 days when the RRF was increased to 500 and 10,000, respectively. With the increase of plugging strength, the remaining oil regions kept decreasing, and they almost disappeared when the RRF increased to 500 (KR was reduced from 10,000:3 to 20:3), as seen from Fig. 20. The injected CO_2 was diverted to these regions to displace the remaining oil. Therefore, CO_2 saturation in these regions was increased, as is shown in Fig. 21.

The dashed lines in Fig. 22 exhibited the oil recovery performance at different RRFs. A higher oil recovery was achieved when the RRF values were higher. The results were consistent with the observations in Figs. 20 and 21. The results demonstrated that conformance treatments were effective to improve the oil recovery

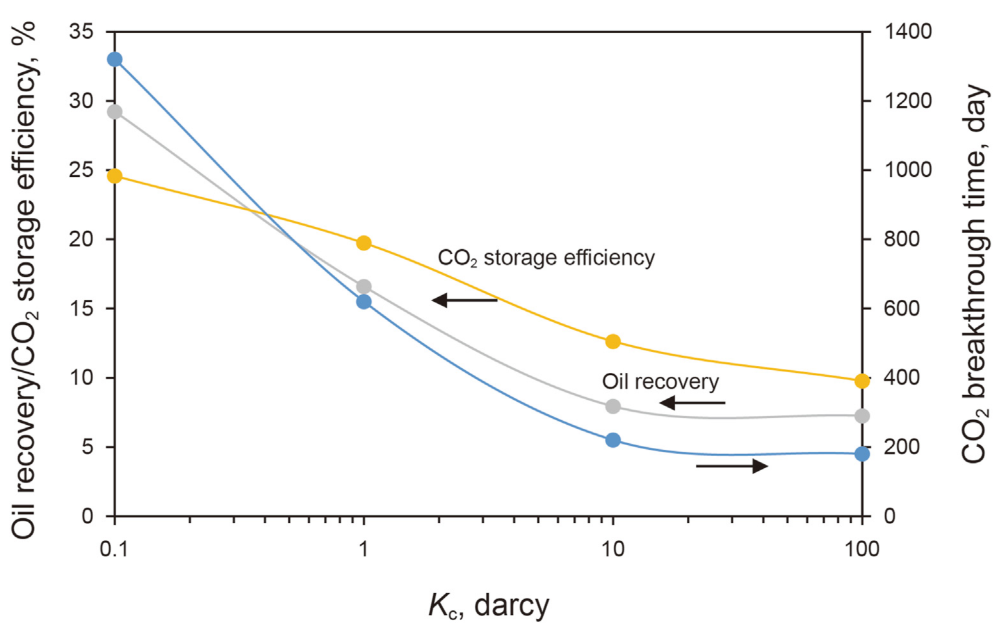


Fig. 12. Impact of channel permeability (K_c) on CO_2 breakthrough, oil recovery and CO_2 storage efficiency.

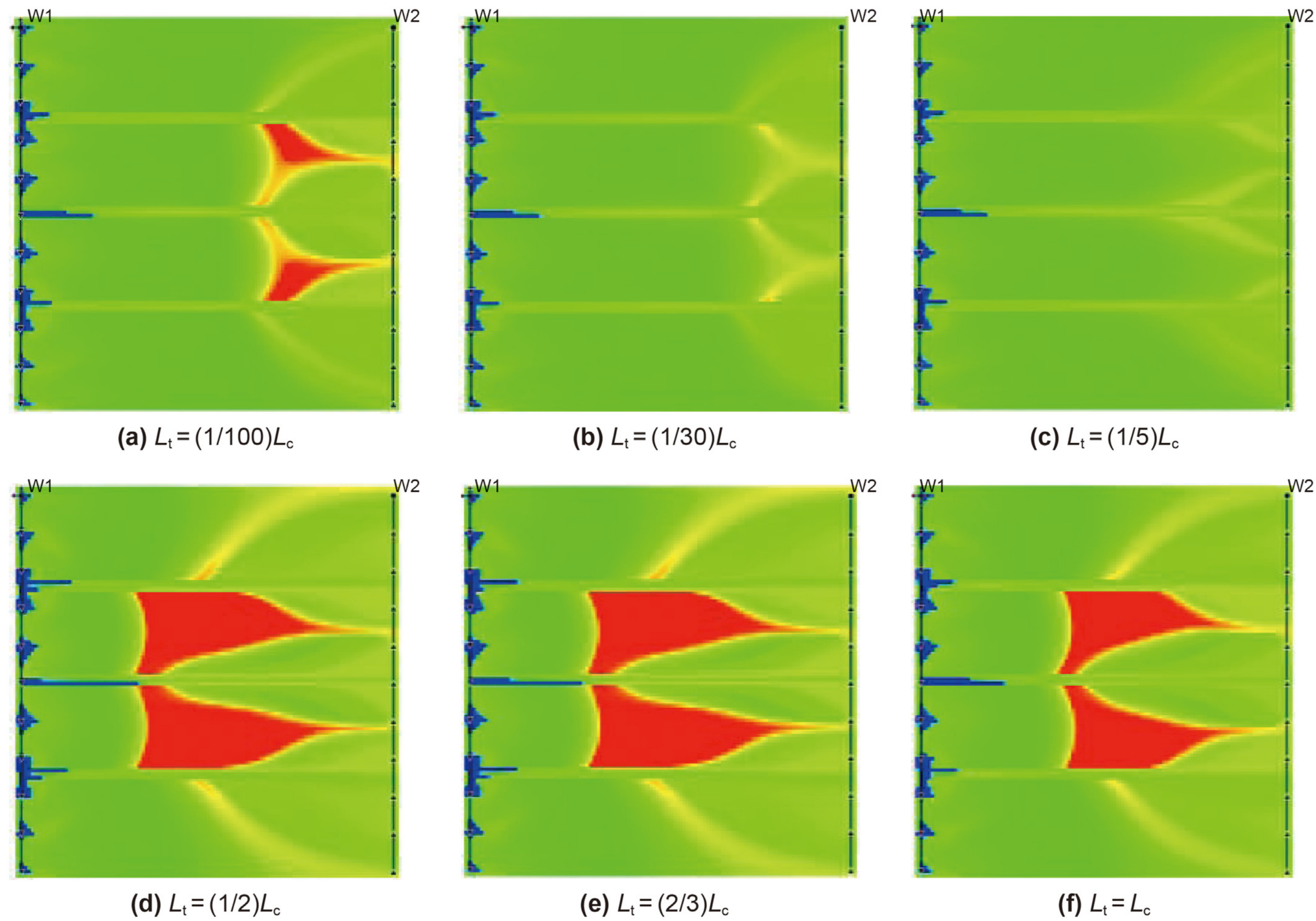


Fig. 13. Effect of treatment size (L_t) on remaining oil saturation distribution.

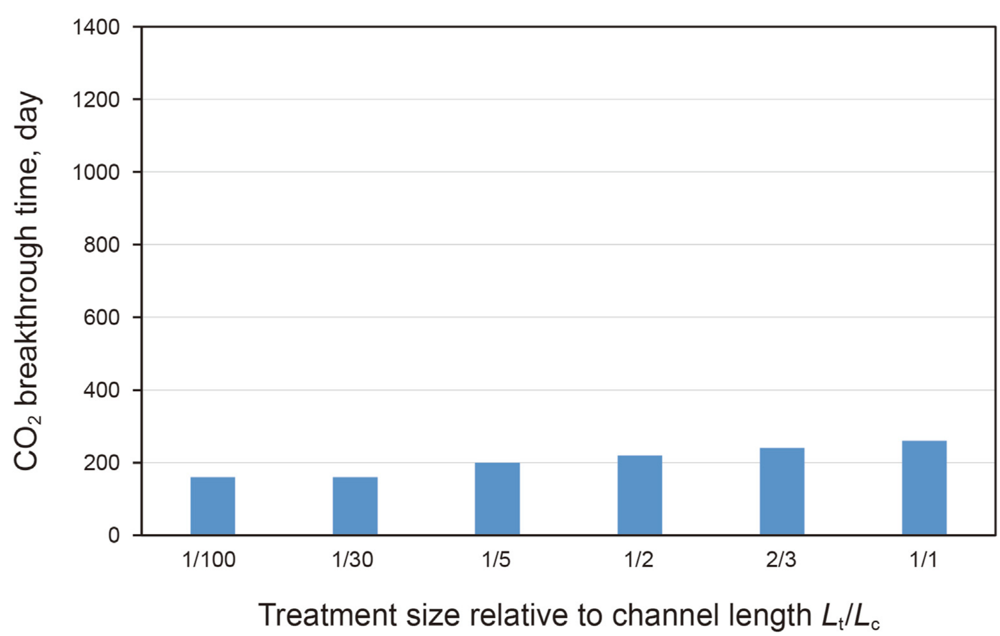


Fig. 14. CO_2 breakthrough times with different treatment sizes.

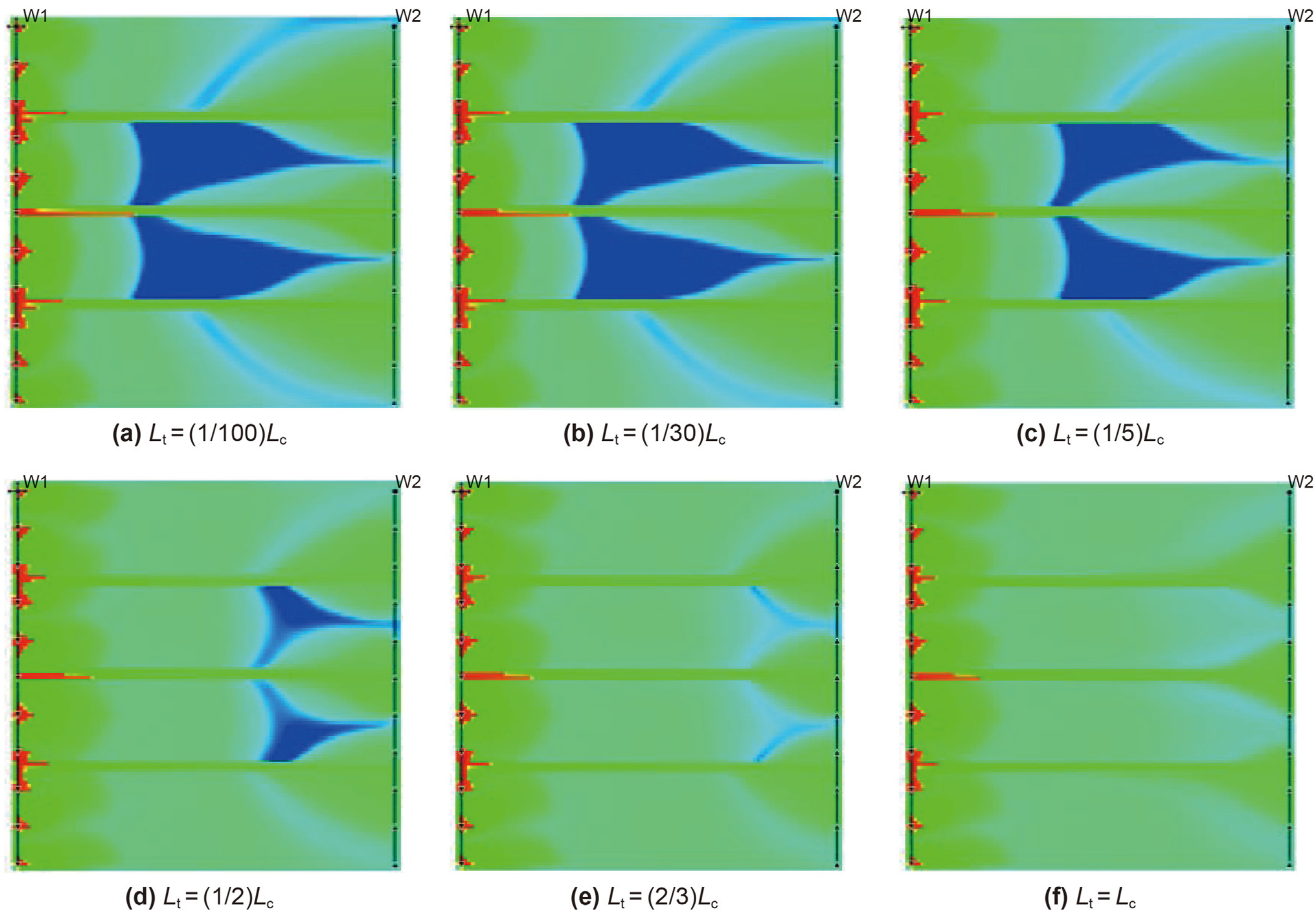


Fig. 15. Effect of treatment size (L_t) on saturation distribution of sequestrated CO_2.

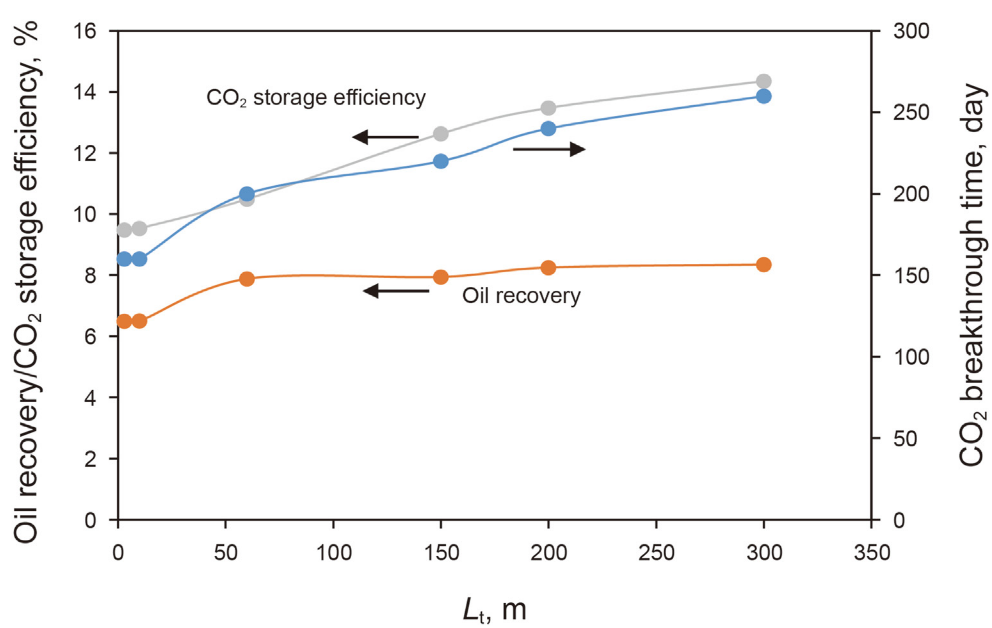


Fig. 16. Effect of treatment size (L_t) on ultimate CO_2 channeling (i.e., represented by breakthrough time), oil recovery and CO_2 storage.

in CCUS-EOR projects. In the case studies, after 10 years, with a conformance treatment of RRF = 500, 10.3% OOIP additional oil was recovered compared with the case of RRF = 3. When the RRF increased from 3 to 30, the resulting oil recovery improved slightly,

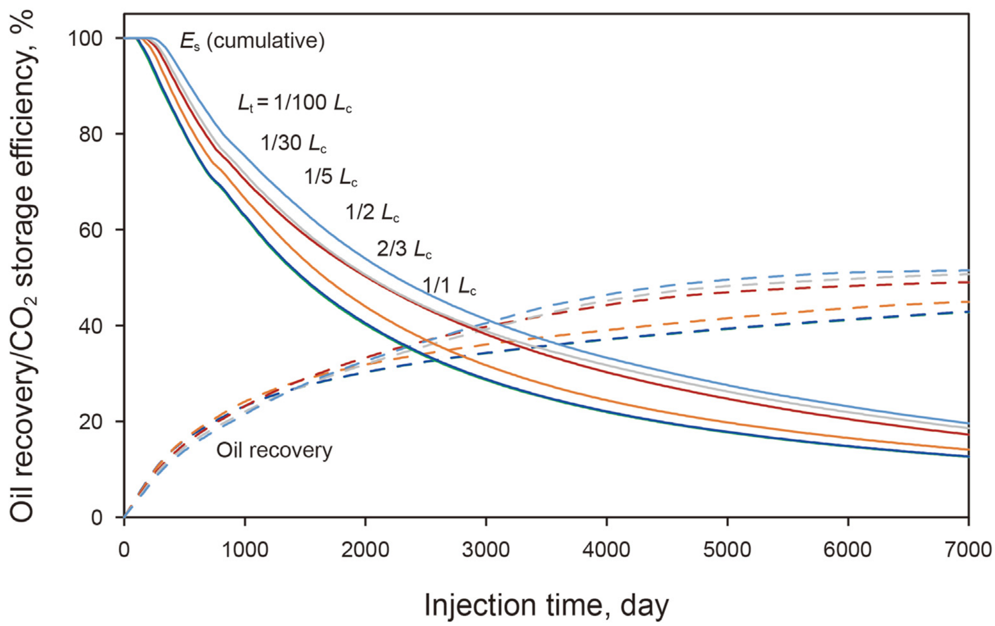


Fig. 17. Effect of treatment size (L_t) on oil recovery and CO_2 storage.

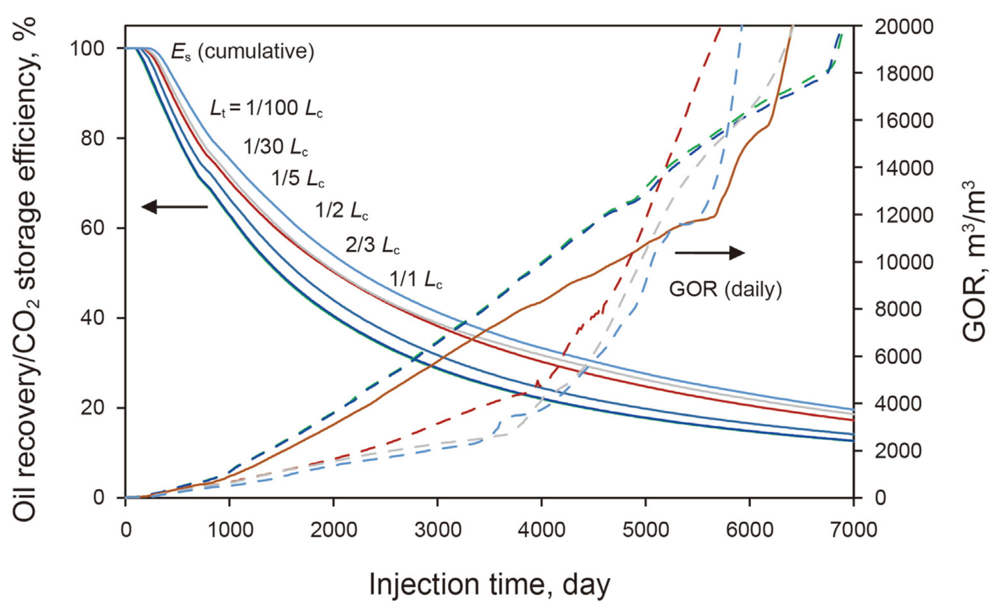


Fig. 18. Effect of treatment size (L_t) on daily GOR and CO_2 storage.

indicating insufficient plugging of the gel materials to the channels. Therefore, the treatment was not effective in terms of the oil recovery improvement. The results clearly indicated the requirement on the plugging strength of conformance treatments to achieve satisfactory oil recovery improvement in CCUS-EOR projects. As shown in Fig. 23 (dashed lines), producing GOR increased faster as the RRF values were lower. Higher GORs were not favorable for oil recovery and CO_2 storage. High GORs indicated poor dynamic CO_2 storage efficiency, as illustrated by the solid lines. The results emphasized the requirement on the RRF to achieve favorable GORs in CCUS-EOR projects. With a higher RRF, a better storage efficiency was achieved. The results in Figs. 21–23 clearly demonstrated that proper conformance treatments could significantly increase the CO_2 storage capacity and efficiency. Variations of the behavior of CO_2 channeling (breakthrough), oil recovery, and CO_2 storage along with the RRF were also summarized in detail in Fig. 24. A weak treatment (e.g., RRF < 100, KR > 100:3 after treatment) could not effectively address the CO_2 channeling problem. The treatment should establish a sufficient plugging strength (i.e., reducing the channel permeability to an extent of KR below 100:3, ≈30 in this study) to exert a reliable resistance to the CO_2 channeling flow. In field applications, gels could degrade after long-term contact with CO_2 (usually in supercritical conditions). This behavior explains why the RRF was significantly reduced in subsequent cycles during water-alternating-gas (WAG) injection processes. The results of this study emphasized the importance of long-term stability of the conformance treatment materials placed in the channels. The results demonstrate the importance of conformance treatment in

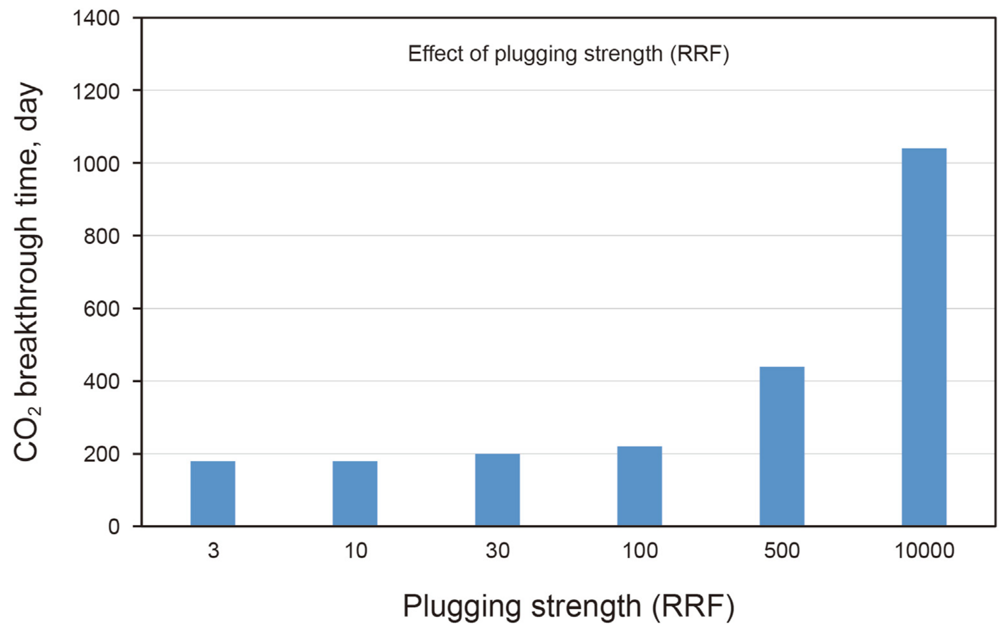


Fig. 19. CO_2 breakthrough times at different plugging strengths.

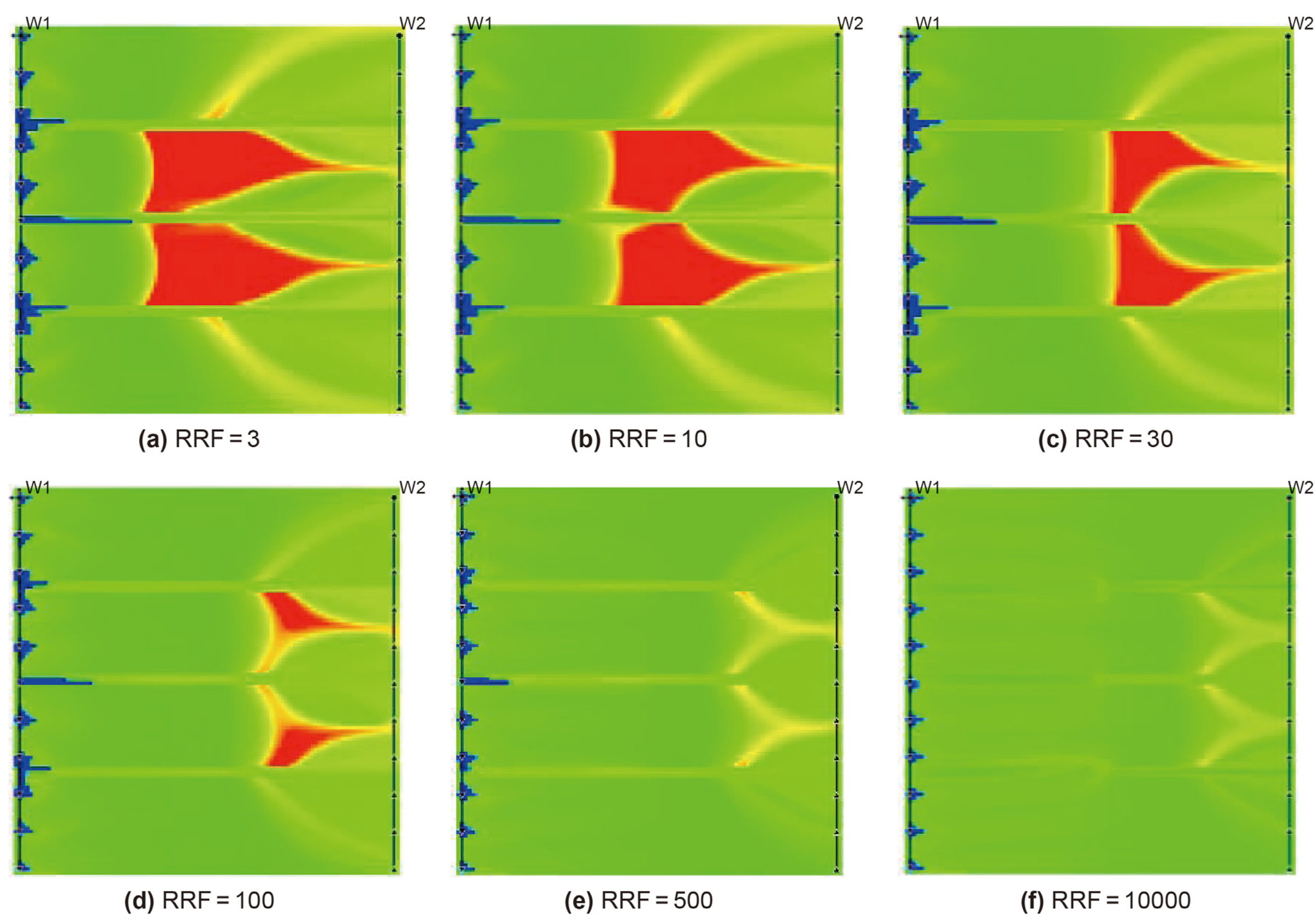


Fig. 20. Effect of plugging strength (RRF) on remaining oil saturation distribution.

maximizing the performance of coupled objectives of CCUS-EOR process to achieve both oil recovery improvement and efficient carbon storage.

Compared with the treatment size, the CO_2 storage efficiency

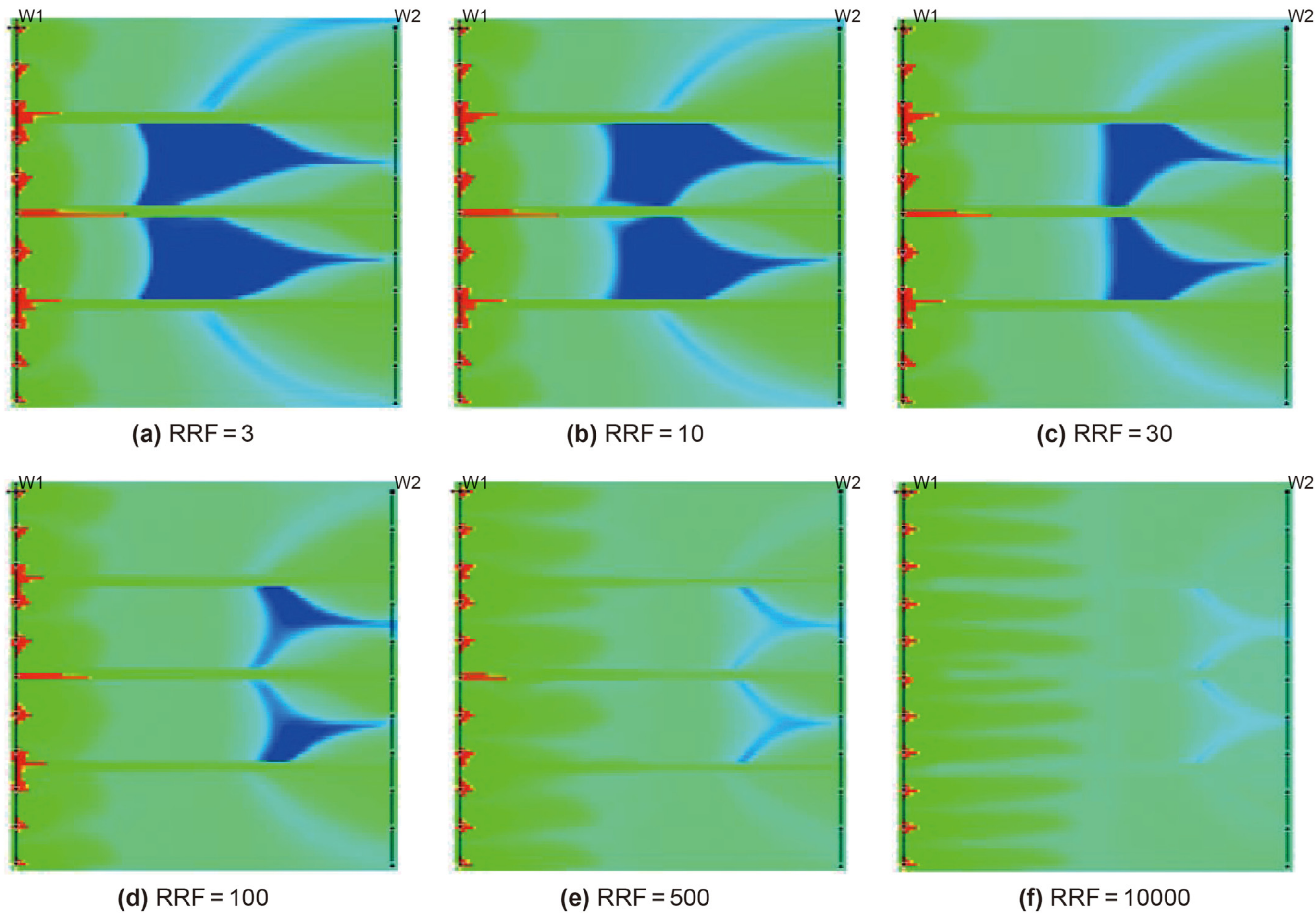


Fig. 21. Effect of plugging strength (RRF) on saturation distribution of sequestrated CO_2.

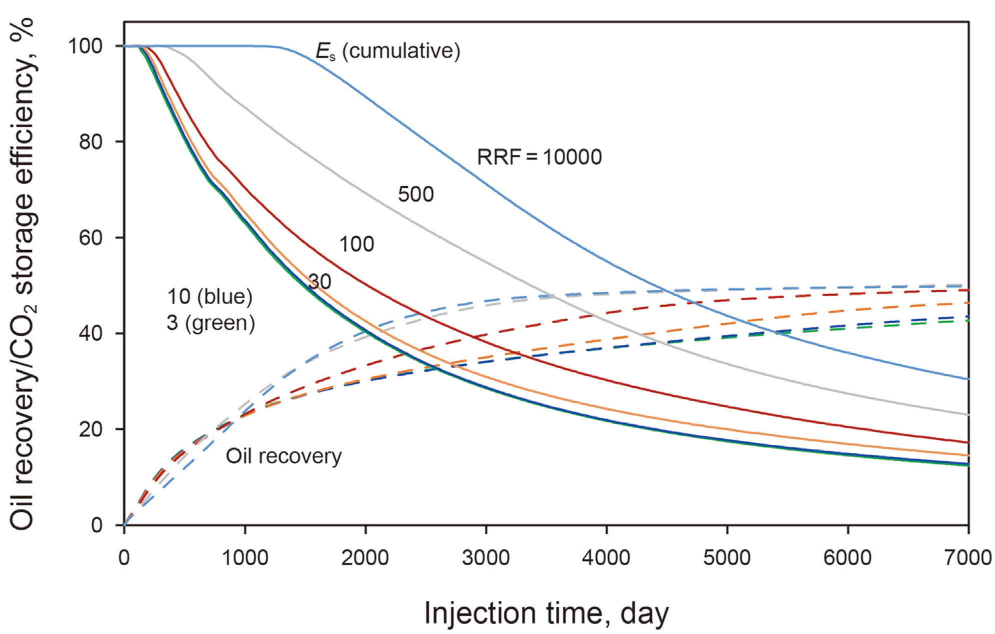


Fig. 22. Effect of plugging strength (RRF) on cumulative oil recovery and CO_2 storage.

was more sensitive to the plugging strength of the conformance treatment materials (Fig. 23 vs. Fig. 19). This observation was important for conformance treatment design in CCUS-EOR projects. According to this study, the materials should reduce the channel

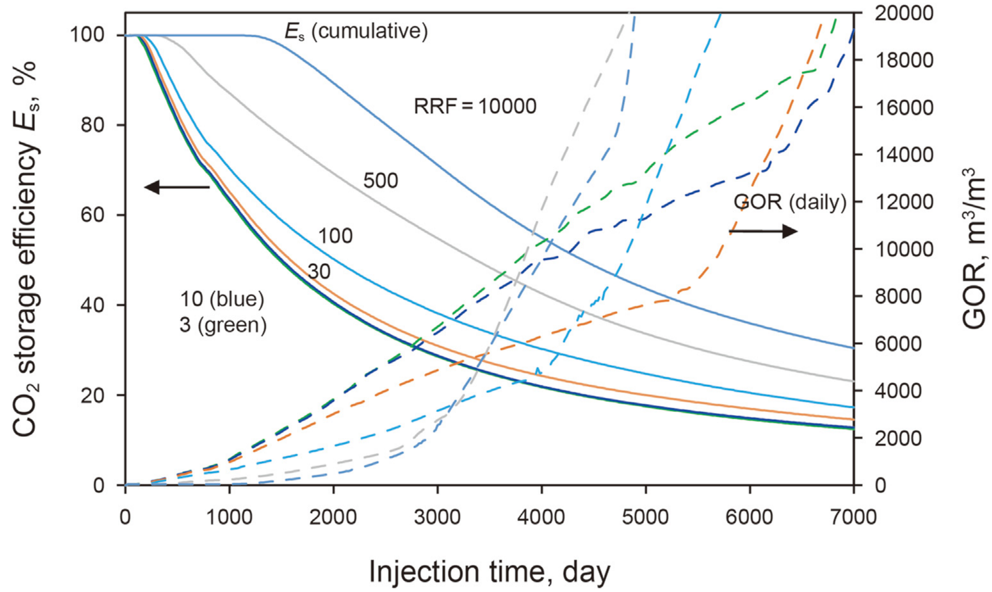


Fig. 23. Effect of plugging strength (RRF) on daily GOR and CO_2 storage.

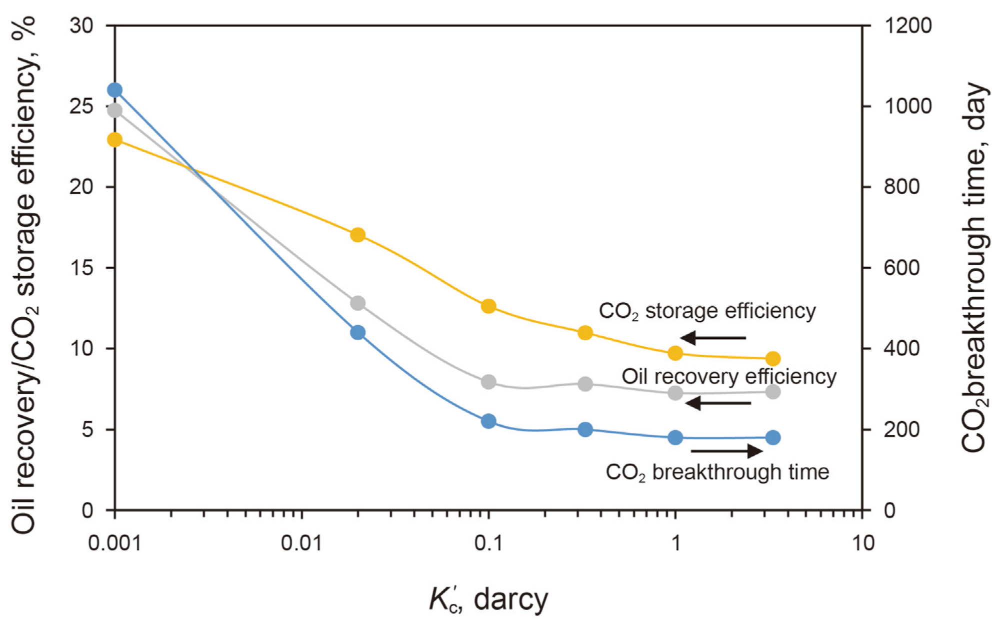


Fig. 24. Effect of plugging strength (RRF) on ultimate CO_2 channeling, oil recovery and CO_2 storage.

permeability to make the KR below 30. In this study, the gel materials were assumed selectively placed in the high-permeability channels without penetrating the reservoir matrices. The selective placement behavior depends on the matching properties between the reservoir and the gels, especially the particle/pore matching size relationship and gel strength. The gels cannot enter the matrices because the pore size of the matrices is too small. Instead, the gel materials can selectively enter the high-permeability channels due to the large pore size in the channels (Zhao and Bai, 2022c). In conformance treatments, attention should be paid to the surface cake and damage to the matrices. The damage could be removed by acid soaking or other chemical and/or mechanical techniques. Thus, we assumed no matrix damage by the gel treatment in this study. Also, attention should be paid to health safety and environmental impact of the treatments. The gel materials, as in a crosslinked solid state, do not have the ability to migrate to shallow aquifers to contaminate ground water.

The benefits of conformance treatments include delayed CO_2 breakthrough, incremental oil and increased CO_2 storage. Also, the GOR was lowered, reducing the processing cost to separate and recycle the CO_2. A rough economic analysis was performed to evaluate the conformance treatments on CCUS-EOR projects. The economic performance of conformance treatments after 10 years of production in different case studies was summarized in Table 6. In the evaluation, the crude oil price was set at 60 \$/bbl (447.2943 \$/t). The net carbon bonus was set at 50 \$/t. That is, the company could receive a \$50 net bonus when sequestrated one ton of CO_2 underground. In the base case (Case 1), the treatment cost was \$200,000. The cost was lower when the treatment size was smaller or the plugging strength was lower. Taking Case 1 (RRF = 100) as an

Table 6
Economic performance evaluation of conformance treatments (after 10 years).

Factors		Case #	CO_2 breakthrough time, d	Incremental oil recovery, t	Reduced CO_2 production, t	Increased CO_2 storage, t	Benefit from oil gain, USD	Benefit from increased storage, USD	Benefit from reduced CO_2 production, USD	Treatment cost, USD	Total benefit, USD
With/without treatment	Without	case 0	160	0	0	0	0	0	0	0	0
	With	case 1	220	4748	21958	5248	2123905	262384	109791	200000	2296080
Channel permeability (darcy)	100	case 2	180	2002	8509	4177	895602	208873	42544	150000	997019
	10	case 1	220	4748	21958	5248	2123905	262384	109791	200000	2296080
	1	case 3	620	6948	41537	4721	3107892	236059	207685	220000	**3331635**
	0.1	case 4	1320	7726	48497	4153	3455650	207652	242486	250000	**3655787**
Treatment size (L_t/L_c)	1/100	case 5	160	2035	7754	4365	910207	218245	38770	100000	1067221
	1/30	case 6	160	2065	8142	4360	923717	217984	40712	120000	1062412
	1/5	case 7	200	2815	12937	4582	1259323	229089	64687	150000	1403099
	1/2	case 1	220	4748	21958	5248	2123905	262384	109791	200000	2296080
	2/3	case 8	240	4962	24255	4913	2219459	245660	121275	250000	2336393
	1/1	case 9	260	5477	26576	4896	2449926	244785	132882	300000	2527593
Plugging strength (RRF)	3	case 10	180	1987	7646	4272	888696	213601	38229	130000	1010526
	10	case 11	180	1993	8422	4114	891602	205695	42112	150000	989409
	30	case 12	200	2592	13068	4227	1159392	211361	65338	180000	1256091
	100	case 1	220	4748	21958	5248	2123905	262384	109791	200000	2296080
	500	case 13	440	6747	36681	5357	3017697	267850	183406	250000	**3218953**
	10000	case 14	1040	6964	46187	3797	3114836	189867	230936	300000	**3235638**

Note: Oil price: 60 \$/bbl = 447.2943 \$/t; Processing cost of produced CO_2: 5 \$/t; Net carbon bonus: 50 \$/t.

example, as mentioned earlier, the CO_2 breakthrough time was delayed from 160 days to 220 days compared with the case without conformance treatments (Case 0). The incremental oil recovery was 4748 t, and the CO_2 storage was increased by 5248 t. Also, 21,958 t of less CO_2 was produced after conformance treatment. The total benefit from the treatment was 2.296 million dollars. The benefits increased with treatment size and plugging strength. The effect of net carbon bonus on the overall economic performance was shown in Figs. 25 and 26. Obviously, the overall benefit increased with the net carbon bonus. A negative value means the company received bonus could not offset the expense to purchase the carbon source. There was even a deficit when the net carbon bonus was too low. The plots can help identify favorable treatment conditions to maximize the economic benefits.

Above all, the results demonstrate that conformance treatment is an effective strategy to help achieve the coupling goal of oil recovery and carbon storage during CCUS-EOR process.

4. Conclusions

The importance of conformance control was systematically investigated to achieve the synergy of enhanced oil recovery (EOR) and CO_2 geo-sequestration. CO_2-resistant polymer gels were introduced to seal off the high-permeability channels and establish in-depth conformance control of the CO_2 flow in reservoirs. The results indicated that after conformance treatments, the CO_2 channeling problem was mitigated during CO_2 flooding and storage. The injected CO_2 was more effectively utilized to recover the

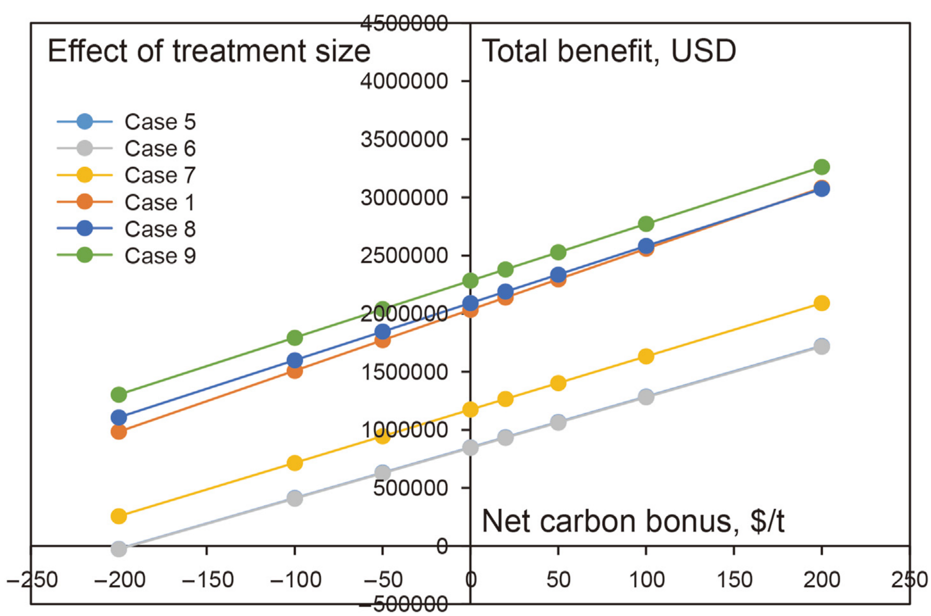


Fig. 25. Effect of treatment size on economic performance at varying net carbon bonus.

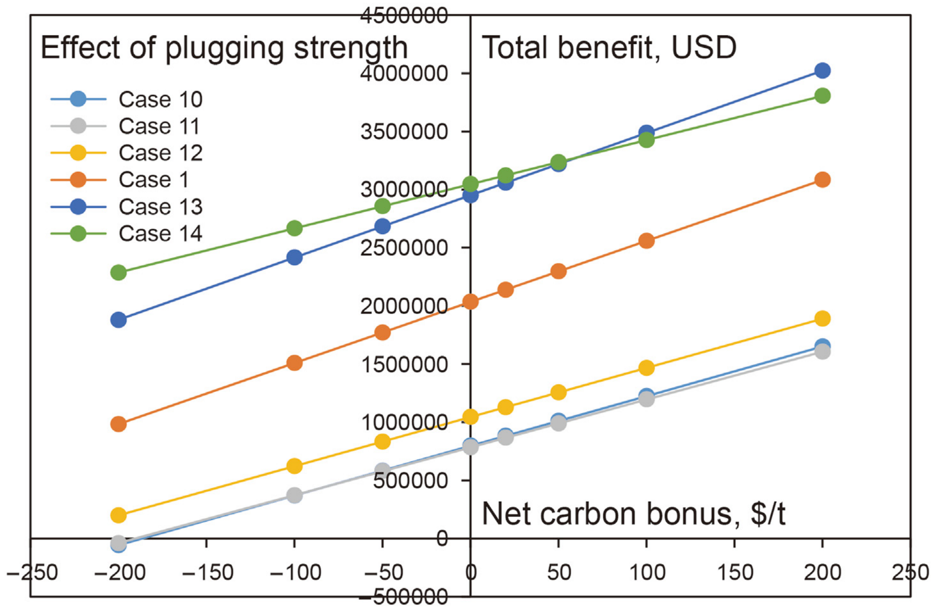


Fig. 26. Effect of plugging strength on economic performance at varying net carbon bonus.

hydrocarbon, and entered more pore spaces. Consequently, more CO_2 was trapped underground. Key parameters on the synergistic objectives of EOR and CO_2 storage were identified. Compared with the treatment size, the CO_2 storage efficiency was more sensitive to the plugging strength of the conformance treatment materials. This observation was important for conformance treatment design in CCUS-EOR projects. According to this study, materials should reduce the channel permeability to make the KR below 30. The results demonstrate the importance of conformance treatment in maximizing the performance of CCUS-EOR process to achieve both oil recovery improvement and efficient carbon storage. This study provides guidelines for successful field applications of CO_2 transport control in CO_2 geo-utilization and storage.

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