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Review

Inspirations from Field-Reservoir CO_2 Flooding with Different Miscible Degrees under Cross-Scale Oil Reservoir Conditions

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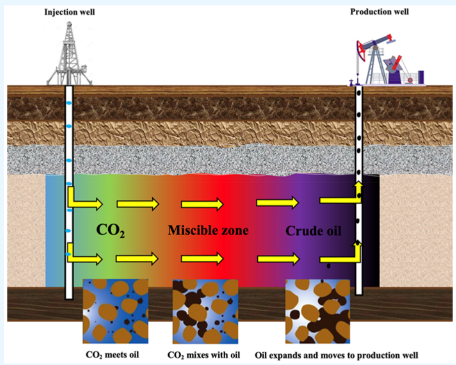
ABSTRACT: In recent years, CO_2 flooding has become one of the main enhanced oil recovery (EOR) methods, especially for tight formations in different oilfields around the world. Most of the CO_2 flooding projects carried out in the world are based on miscible flooding, however, this technique is less effective in China because of the depth of the reservoirs and the heavy components of the crude oil. Near-miscible flooding and immiscible flooding have also been gradually applied to China's domestic oil fields, and have achieved certain oil increase effects, but there are still some challenges such as gas channeling, corrosion, and solid phase deposition in the process of CO_2 flooding. In this paper, through a detailed review of recent domestic and foreign cases of enhanced oil recovery, the effects of development methods of low permeability and ultralow permeability reservoirs under different miscible degrees are analyzed, and the solutions to some of the existing problems in field tests and experience are systematically summarized. According to the results of field tests, both miscible flooding and near-miscible flooding have similar effects and can achieve better recovery increment, with a long effect period and slow gas breakthrough speed. In addition, the problems of gas channeling, corrosion, and solid phase deposition occurring in the process of CO_2 flooding are analyzed, and solutions such as a change in injection methods and coatings are put forward, which effectively promote the development of CO_2 flooding technology. Those suggestions are of great significance for improving the oil recovery rate of unconventional oil reservoirs, ensuring the national energy supply, and low-carbon emissions reduction in China.



1. INTRODUCTION

In the process of reservoir development, EOR technology based on gas injection is used to increase oil production by injecting gas into the reservoir. Gas flooding has the effect of sufficient replenishment of energy, large utilization of crude oil, and high reservoir production. According to the classification of oil development media, it can be divided into hydrocarbon and nonhydrocarbon, and the nonhydrocarbon media mainly includes CO_2, N_2, etc. Among them, CO_2 flooding has the advantages of dissolution and expansion, viscosity reduction, extraction, improvement of mobility ratio, and reduction of oil—water interfacial tension, which have obvious advantages compared with traditional water flooding. CO_2 flooding enhanced oil recovery (CO_2-EOR) technology has wide adaptability, which can realize the recycling of produced gas and can bury greenhouse gases, etc., which is the favorite direction in gas flooding.[1]

CO_2 injection miscible flooding technology began in 1958 in the United States (U.S.), after more than 60 years of rapid development. The theory and technology have been relatively mature since the 21st century and the global oilfield implementation effect is remarkable.[2,3] In 2016, the global EOR output totaled 1.17×10^8 t, of which gas flooding accounted for 31%, and the CO_2 output in the United States reached 23.46 million tons, which indicates that CO_2 injection is not only an effective method of enhanced oil recovery but also has high economic benefits.[4−6]

As shown in Table 1, different from the U.S., oil reservoirs in China have the characteristics of fewer gas sources, deeper depth, and higher content of heavy crude oil components, meaning the domestic oil reservoir CO_2 flooding cannot copy the technical theory and process system of the U.S., resulting in insufficient production.[7−12] In general, the resource conditions suitable for CCUS-EOR in the U.S. are superior, there are commercially successful CO_2 flooding projects in both low and high-permeability reservoirs in the U.S., which proves that the

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Table 1. Comparison of CO_2-EOR Conditions and Technology Conditions in China and the United States

country	gas source	sedimentary facies	heterogeneity	reservoir temperature	crude oil properties	crack	MMP	landform
U.S.	natural gas reservoir	marine facies	weak	lower	light oil	weak	low	plain
China	chemical plant capture	land facies	strong	higher	heavy oil	strong	high	mountains, Gobi

Table 2. Basic Parameters of CO_2 Injection Flooding Oil Fields in China

number	oil reservoir field	temperature (°C)	viscosity (mPa·s)	density (kg·m^{-3})	formation pressure (MPa)	MMP (MPa)
1	Fu 14 block, Jiangsu reservoir	76	2.43	0.82	20.90	21.60
2	Color 9 block, Tuha reservoir	76	1.00	0.75	21.27	21.60
3	Caoshe block, Shengli reservoir	110	7.02	0.87	35.94	29.34
4	BZ25-1 block, reservoir	147	1.13	0.87	55.00	32.84
5	Fan142 block, Shengli reservoir	130	20.40	0.88	44.87	31.65
6	Hei59 block, Jilin reservoir	99	1.85	0.76	24.50	22.30
7	Gao891 block, Shengli reservoir	126	11.83	0.86	42.00	28.94
8	Hei79 N block, Jilin reservoir	97	8.30	0.85	23.60	22.80
9	Huang3 block, Changqing reservoir	85	1.81	0.73	21.70	20.78
10	Hei79 S block, Jilin reservoir	95	1.79	0.78	18.00	22.50
11	Y101 block, Daqing reservoir	105	3.60	0.79	22.10	32.20
12	Chujialou reservoir	108	3.58	0.80	27.45	/
13	Yaoyingtai reservoir	98	1.91	0.78	22.00	26.63
14	Wuqi reservoir	60	2.40	0.78	20.40	29.00

reservoir resources suitable for CO_2 flooding are huge. The U.S. Department of Energy released a report in 2006 indicating that there are more than 12 billion tons of geological reserves suitable for CO_2 flooding. The giant gas reservoirs transported more than 70% of the oil displacement gas through the pipeline transport network and established a diversified CO_2 supply system, which completely solved the gas source problem. The evaluation of the crude oil and CO_2 source is conducted about every five years in the U.S., which provides an important basis for CCUS source matching and gas pipeline network construction, which promotes the sustainable development and application of CO_2 displacement technology in the U.S..[13]

However, as for China, the problem of CO_2 source supply is prominent. The scale of available carbon sources in China's major oil companies is small and scattered, the external carbon source market has not yet formed, the price is high and uncontrollable, and the pressure of supply protection is great. Besides, the lack of transportation pipe networks between oil reservoirs and CO_2 sources leads to a large number of high-concentration CO_2 gas sources that cannot be converted into oil resources and transported to oil fields, and it is difficult for oil companies to start large-scale CO_2 development and storage projects.[14] The construction and operation of a CO_2 transmission pipe network involves both upstream and downstream enterprises of cross-industry and also involves the relationship between local enterprises, which is difficult to accomplish overnight. In addition, the effect of CO_2 flooding technology is not clear. The single well production of low permeability reservoirs in China is low, and the increase rate of production after gas injection is 50%~100%, but the absolute increase is still low. In addition, low oil prices are not conducive to the promotion of CO_2 flooding and storage technology. CO_2 flooding and storage projects have the characteristics of having high technology and being capital intensive, the demand for capital in the early stage of the project is large, the investment payback period is long, and it is difficult to promote the application of CCUS-EOR technology under low oil prices. In addition, most of the CO_2 flooding and storage projects in China are continued from demonstration projects, and there are generally small scales, difficulty in matching various resources, and accumulation and improvement during construction and practice.[15−17]

In general, CO_2-EOR technology in China has experienced four stages: the introduction of CO_2 flooding theory and technology was mainly based on indoor research from 1960 to 1980; the period from 1980 to 1990 was a CO_2 huff and puff test in a single well, and the field crude oil production was considerable. In November 1989, China Oil and Gas Company took the lead in carrying out a CO_2 single well huff and puff test in the Su 88 Well, and the results were obvious. By the beginning of the 21st century, China entered the pilot test stage of CO_2 flooding and systematically studied the supporting technology of CO_2 flooding. Among them, the pilot test time of the Taizhou Formation reservoir in the Caoshe Oilfield of East China Petroleum and Gas Company of Sinopec has been the longest, which has formed a complete injection-production supporting technology and achieved remarkable results. Around 2000, Jiangsu oilfield, Jilin oilfield, and Daqing oilfield successively carried out several well group scale experiments to further explore or verify the feasibility of enhancing oil recovery by CO_2 flooding in various types of reservoirs and obtained many important results. At present, CO_2 flooding has entered a stage of large-scale promotion and application in China. Under the guidance of climate change policies, the concept of carbon capture, utilization, and storage has been formed. In the past decade, China has initially formed a unique CO_2 flooding and storage supporting technology, and several representative CCUS-EOR demonstration projects have been completed.[18−22]

As shown in Table 2, most of the reservoirs in China belong to continental deposition, and the MMP between crude oil and CO_2 is high, most of the reservoirs cannot realize miscible flooding, which seriously hinders the application of CO_2-EOR technology.[23]

As shown in Table 3, the purpose of this work is to analyze the development rules of CO_2 flooding for cross-scale reservoirs with different miscible degrees. In addition, the latest project of the in situ CO_2 flooding mechanism and technology is analyzed in this work, and the implementation and application effects of

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Table 3. Differences between This Work and Previous Works

	major content			
author	reservoir cases of diffrenet miscible types	reservoir cases of diffrenet pore sizes	summarize problems and propose solutions	reservoir name
Qin[3]	no	no	no	
Jiang[7]	no	no	yes	
Wang[42]	immiscible	no	no	Changqing
Li[1]	yes	no	yes	Caoshe, Shengli, Yaoyingtai
Lou[21]	immiscible	no	yes	Jilin
Chen[17]	yes	no	no	Jilin
Mohan[2]	no	no	yes	
Guo[59]	immiscible	no	yes	Yanchang
Zhang[46]	no	no	no	
Zhang[46]	yes	tight reservoir	no	Eerduosi, Daqing, Changqing, Weibei
Zhang[53]	no	no	yes	Jilin, Daqing, Changqing
Liu[20]	yes	yes	no	Daqing, Jiangsu, Chujialou, Caoshe, Liaohe
this work	yes	yes	yes	More than 20 resevoirs

CO_2 flooding projects in China and abroad under different miscible levels of reservoirs are also evaluated. In addition, the problems in some field applications of CO_2 flooding are summarized and evaluated in this work. On this basis, the effective solutions to the problems existing in the process of CO_2 flooding development are put forward, which provides a reference for the further development of CO_2 flooding technology under different miscible degrees.

2. RESULTS

2.1. Development Characteristics of Different Miscible Degrees. Due to the characteristics of domestic reservoirs in China, most of the reservoirs can not reach the miscible degree. By comparing the development effects of CO_2 flooding reservoirs under different oil and gas miscible states, the field application technology is summarized, then the CO_2 flooding technology means for different reservoirs is analyzed.

2.1.1. The Pore-Scale Effect on the Development Characteristics under Miscible Conditions. 2.1.1.1. The Development Characteristics in Low Permeability Reservoir. (1) Taizhou Formation, Caoshe Oilfield, Subei Reservoir. The average burial depth of Taizhou formation reservoir in southern fault block of Caoshe oilfield is 3020 m, the oil-bearing area is 0.703km^2, the geological reserves are 142 × 10^4 t, the recoverable reserves are 59 × 10^{4}t, the average reservoir porosity is 14.8%, the permeability is 46.0 × 10^{-3}μm^2, the formation dip Angle is 10° ∼ 15°, and the reservoir temperature is 104 °C. The density of crude oil is 0.879 g/cm^3, and the viscosity of crude oil is 12.80 mPa ·s, which is a massive sandstone reservoir. The reservoir pressure before gas injection is 32.06 MPa and the MMP between crude oil-CO_2 is 29.34 MPa, which belongs to the development of CO_2 miscible flooding.[24]

In September 2007, the gas injection was carried out in the main part, and the distance between the injection and production wells was about 250m. The method of alternating water and gas after continuous gas injection was adopted. There are 6 gas injection wells and 15 production wells in the test area, with a cumulative gas injection of 20.8 × 10^4 t and a cumulative oil increase of 11.60 × 10^4 t. In 2017, a secondary gas injection test was carried out in the test area to explore the feasibility of enhanced oil recovery after CO_2 injection. As of December 2020, the secondary gas injection test has accumulated 8.2× 10^4 t of gas and 1.92 × 10^4 t of oil, as shown in Figure 1.

With the continuous increase of CO_2 injected, the reservoir output of Taizhou formation in the Caoshe oilfield continues to rise, but gas channeling occurs along the main direction, which seriously affects the development. Therefore, adjustment countermeasures to prevent gas channeling, including injection and production structure adjustment, injection mode adjustment, injection parameter adjustment, and injection profile adjustment, have been formulated, which are mainly as follows:

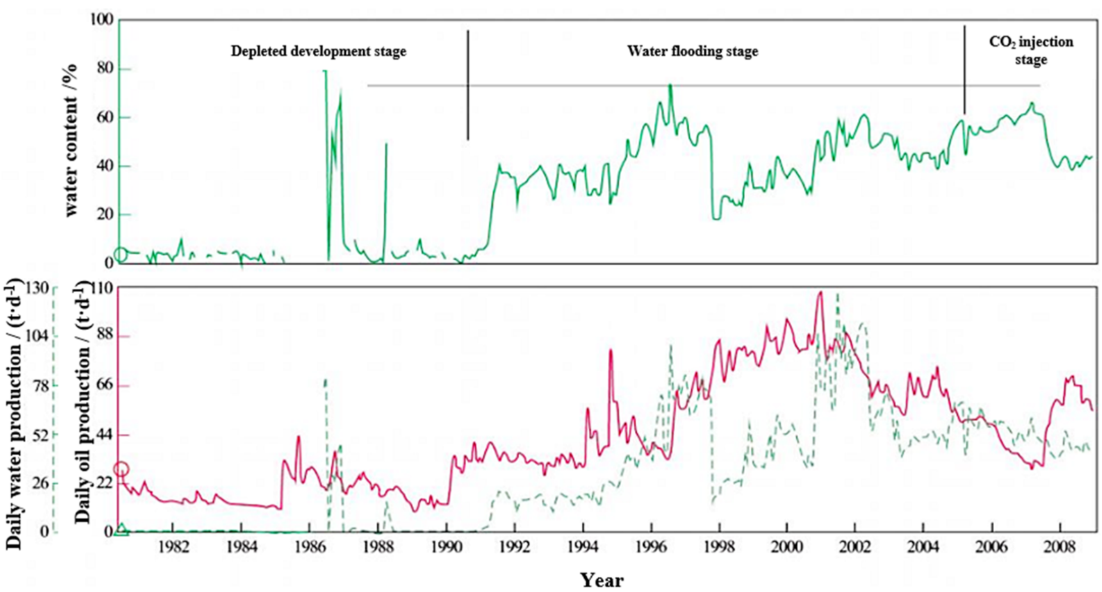

Figure 1. CO_2 extraction effect of Taizhou Formation in Caoshe Oilfield.

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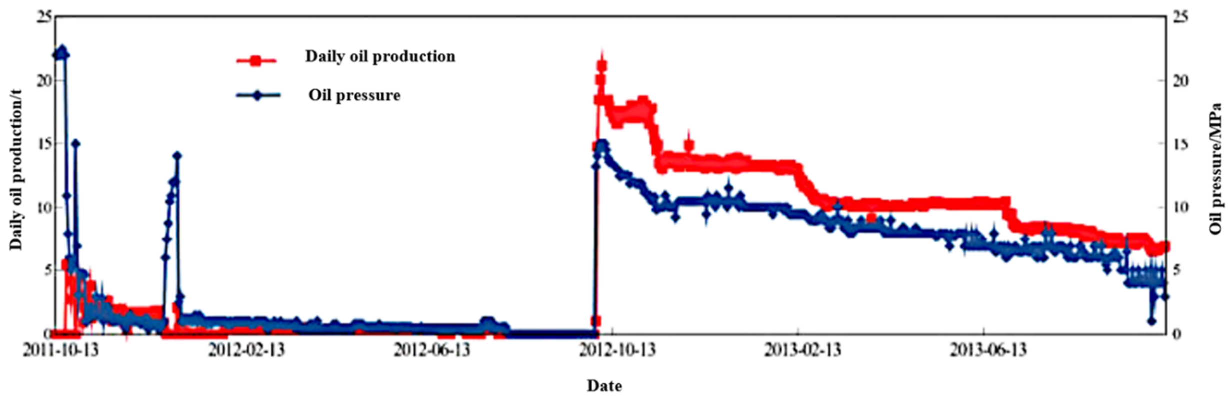

Figure 2. Daily oil production and pressure curves of well Hu 96−3 in Zhongyuan Oilfield.

(1) Injection and production structure adjustment: the formation inclination of the reservoir in Taizhou formation is 9° ∼ 14°, and the effect of using gravity to improve the displacement efficiency and oil recovery efficiency is more favorable than that of horizontal reservoirs. Therefore, a production well was adjusted to transfer gas at the high part of the structure to reduce the loss of CO_2 and ineffective gas injection.
(2) Injection mode adjustment: after gas channeling, water−gas alternations are adopted, the gas-oil ratio of production Wells is significantly decreased, the output is increased, and the gas−water alternations are initially effective.
(3) Adjustment of injection parameters: due to strong heterogeneity and high permeability bands, large-area gas channeling occurs after injection, so the injection volume and injection speed are reduced in the middle and late period, that is, the HCPV of CO_2 injection is increased from 22% to 30%.
(4) Injection profile adjustment: the combination slug plugging control process was used to inject a high-temperature plugging agent formulation system. After profile control, the shut-in pressure slowly decreased, and the curve was gentle, which played a plugging role.

The results show that gas channeling is controlled by adjusting the four aspects, and the reservoir gas-oil ratio decreases from 2733.1m^3/ m^3 to 63.84m^3/m^3. The oil increase effect was further expanded, and the daily oil production reached its peak, increasing from 30.72 t before gas injection to 81.68 t after gas injection.

(2) Hu 96 Test area, Zhongyuan Oilfield reservoir. Hu 96 is a deep pressure, low permeability, and high volatility reservoir with a buried depth of 3800−4400 m, formation pressure of 75 MPa, pressure coefficient of 1.7, formation temperature of 148 °C, porosity of 15.3%, permeability of 4.85 × $10^{-3}\mu m^2$, and crude oil saturation pressure 37.68 MPa. The surface crude oil density is 0.8046 g/cm^3, the dissolved gas-oil ratio is 413.28 m^3/m^3, and the total salinity of formation water is 34.32 × 10^4 mg/L. Oilfield development water injection can not be injected, the reservoir energy is low.[25,26]

In 2010, the CO_2 flooding pilot test was carried out in well Group Hu 109, as shown in Figure 2. Before the test, the formation had no energy supplement, the oil production decreased rapidly, the daily production of crude oil was 0.4t, and the pressure of formation was 0.6 MPa, and the designed daily injection of CO_2 was 30 t. By the end of August 2013, the cumulative injection of CO_2 was 15199.3 t and the formation pressure was restored from 28.5 to 48.5 MPa. On this basis, the formation energy was sufficient, the daily output of crude oil was up to 21.2t the cumulative production of crude oil increase was up to 3780 t, and the gas increase was 210 × 10^4 m^3.

2.1.1.2. The development characteristics in ultralow permeability reservoir. (1) The Fan 142 Well Group in Shengli Oilfield Reservoirs. The oil-bearing area of the Fan 142 well group in Shengli oilfield reservoirs is 0.94 km^2, and the test oil-bearing layer is sand group 1, upper submember of Sha4Member, with geological reserves of 32.6 × 10^4 t and a permeability of 1.2 mD. Bar sand developed in the northeast, and beach sand was developed in the southwest. The reservoir thickness of the effective production well in the eastern bar sand area is large, the physical property is good, and the accumulation of crude oil before the gas injection is greater. The sedimentary facies are the main factor affecting the gas drive effect of the well group, and the production wells with the injection-production spacing of 243−494 m in the bar sand area are affected. Well-group gas injection wells and production wells implement "direct reading with storage" continuous pressure monitoring to continuously track formation pressure changes. It was found that the formation pressure recovered significantly, and the average pressure recovered from 14.2 MPa before gas injection to 39.0 MPa. The three eastern wells successively reached MMP in 2015, and the wells entered the full gas drive development stage after December 2016.

Gas injection began in June 2013, and the formation pressure before gas injection was 17 MPa. Six oil wells were shut down to restore formation pressure, and electronic pressure gauges were inserted to monitor the recovery of formation pressure in the oil wells for more than 1800 days. The gas injection rate is 15−30 t/d. By the end of 2016, the cumulative CO_2 injection rate was 1.9 × 10^4 t, the formation pressure of the oil well had recovered to 33.7 MPa (1.07MMP), and miscible flooding (MMP is 31.65 MPa) had been realized. As shown in Figure 3, since November 2016, the three effective oil Wells have been opened one after another, and the daily oil production is 5−6 t/d, which is much higher than the pregas injection production. As of September 2019, the cumulative CO_2 injection volume of the well group was 3.9 × 10^4 t, the cumulative oil increase volume was 0.7 × 10^4 t, the cumulative injection volume was 1.9 × 10^4 t, and the stage oil change rate was 0.37.

(2) The Sha 4 Member of the Shahejie Reservoir. Typical beach-bar sand reservoirs are developed in the Sha 4 Member of the Shahejie Formation in the CL area of the Dongying Sag, China. Recently, the quality of the newly added proven reserves in the Sha 4 Member of the Shahejie Formation kept abruptly

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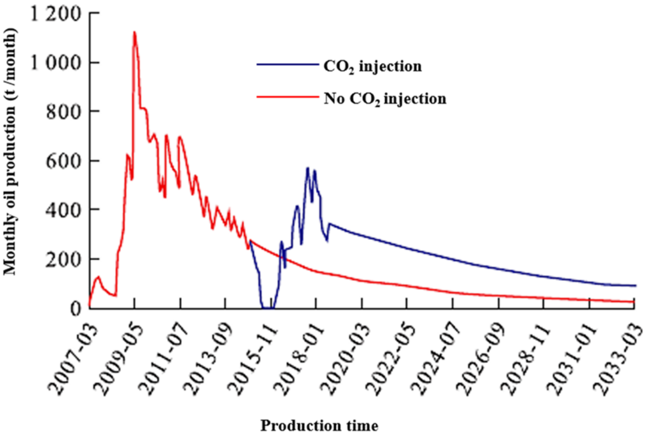

Figure 3. Gas injection production curve.

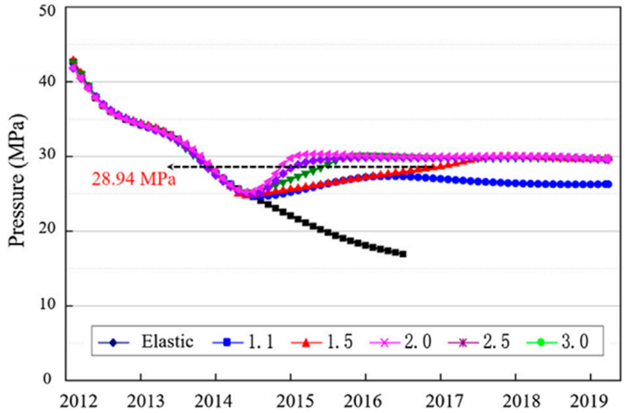

Figure 4. Variation law of designed pressure curves in different oil production rate schemes.

decreasing. It is caused partly by the relatively deep burial depth of the reservoir, and the permeability of the reservoir that drops sharply from 10 to 0.3 mD. Due to the inability to achieve high-efficiency water injection development, oilfield engineers can only select some units with relatively good petrophysical properties to carry out large-scale fracturing.[27,28] The main reservoir of the ultralow permeability beach-bar sand reservoir in the Sha 4 Member of the Shahejie Formation is buried between 2700−3400 m, and its original formation pressure is 32−45 MPa.

The development method that relies solely on elastic energy results in a rapid decline in production and low recovery of crude oil. Therefore, it is necessary to find new energy supplement methods to improve the development level and production degree of low-permeability reservoirs. Therefore, a field test is conducted on Well A1 in the middle of Block 5 for the CO_2 injection test project. This well is surrounded by six production wells where they are spaced by 350 to 700, and the daily gas injection volume is 30−60 m^3, and the gas injection pressure in the initial stage is low and maintained at 2−8 MPa. Except for the well with a distance of 700 m, which was not effective, the other five wells were effective to varying degrees.

After the measured wells in the first stage were effective, the well group expansion began two gas injection wells and 1 production well was newly drilled, forming 4 central gas injection wells and 6 surrounding production wells. After that, the injection-production well pattern was gradually improved, and the overall development of the XX Block was realized. The static pressure measured in Well A1 was 14.78 MPa at the time of transfer injection, and it changed to 25.628 MPa after 2 years, with an increase of 10.848 MPa and an average monthly increase of 0.638 MPa. For another gas injection well of Well A-16, the static pressure measured at the start-up stage was 26.03 MPa, and the static pressure measured after 2 years of gas injection was 28.3 MPa. The injection ratio and the production increase of relationship varying from 1.1 to 3.0 is explained in Figure 4 with pressure change in function of the ratio.

2.1.1.3. The Development Characteristics in Tight Reservoir. The oil-bearing area of the Huang3 Chang-8 block in the Changqing oilfield reservoir is 3.5 km^2, the used reserves are 186.8 × 10^4 t, the average oil layer thickness is 13.0 m, the porosity is 8.3%, and the permeability is 0.27 mD, belonging to the ultralow permeability reservoir class. At the end of 2018, the gas injection scale of "9 injection and 37 production" was formed. Before gas injection, the average daily fluid per well was 2.00 m^3, the daily oil per well was 0.78 t, the comprehensive water cut was 55.7%, and the CO_2 injection could reach 1.2 MMP after water flooding. The gas-oil ratio of crude oil production in the test area is 88.9 m^3/t, the saturation pressure is 10.48 MPa, the formation oil volume coefficient is 1.2782, the formation oil density is 0.7248 g/cm^3, the degassed oil density is 0.8296 g/cm^3, and the oil viscosity is 1.81 mPa·s. The content of light hydrocarbon and intermediate hydrocarbon (C_2−C_{15}) in formation oil is 48.87%.[29]

Due to strong reservoir heterogeneity, fracture development, oil well fracturing and putting into operation, artificial fractures, and water flooding advantageous channels formed over a long period, making the gas channeling risk great during CO_2 flooding. A comprehensive identification standard for gas channeling has been established (Table 4), and a CO_2 flooding classification regulation policy for low permeability reservoirs has been formed (Table 5). After taking measures, the oil increase is expected to be 183 000 tons. The oil recovery increased by 15.1%.

Table 4. Comprehensive Identification Criteria for Gas Channeling in the Test Area

number	producing well condition	produced gas CO_2 content (mol %)	recommended gas-oil ratio (m^3/t)
1	no gas wells	[0, 0.8]	[0, 80]
2	wells with dissolved CO_2	[0.8, 50]	[80, 150]
3	front breakthrough wells	[50, 70]	[150, 325]
4	gas channeling risk wells	[70, 80]	[325, 2000]
5	gas channeling wells	[80, 100]	>2000

2.2. The Miscible Degree Effect on the Development Characteristics. *2.2.1. The Development Characteristics of Oil Reservoirs under near Miscible Conditions.* The reservoir depth of Gao 89−1 block in Zhenglizhuang oilfield reservoirs is 3000 m. The lithology is mainly a gray mudstone interlayer with thin layers of gray, argillaceous, and dolomitic siltstone of varying thickness. The original formation pressure is 42 MPa, the formation temperature is 71 °C, the crude oil viscosity is 1.59 mPa·s, the relative density is 0.769, the average permeability is 2.1mD, and the porosity is 13.1%. The minimum miscible pressure is 28.9 MPa.[30−34]

Table 5. Control Strategies at Different Gas Drive Stages

gas drive stages	dynamic feature	measures and countermeasures	adjusted target
initial response	the plain effect is not uniform some wells are not working	injection and production parameters optimization	keep the miscible phase, improve the effect
full response period	gas-oil ratios are rising in some wells	injection and production parameters optimization	keep miscible phase, control gas channeling
gas blowby period	gas channeling in some wells; yields have a rapid decline	alternation of water and air foam plugging	decrement
	gas channeling in large-scale oil wells; yields have a rapid decline	profile control and plugging system adjustment	decrement

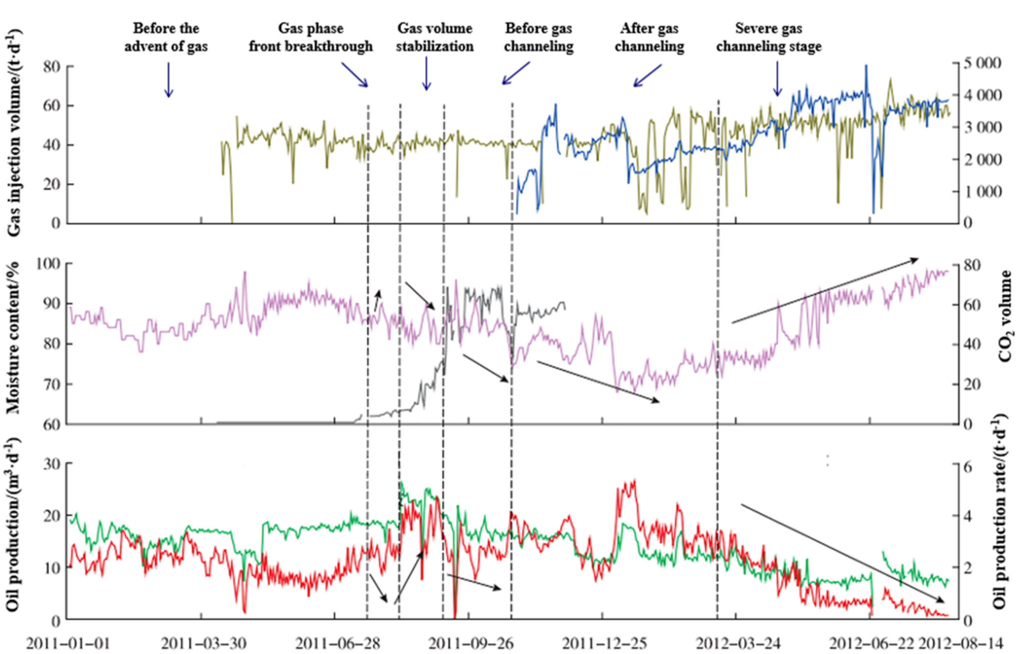

Figure 5. Production curve of typical oil wells.

After the elastic development in the early stage, the pressure dropped to 0.73 MMP, and then advanced CO_2 injection was carried out, and the five-point Fabu well was used, the injection and production methods were four injections and one production. The pressure was restored to 0.9 MMP, and near-miscible displacement was carried out. The oil well suffered an obvious effect, and the cumulative oil volume was 4.9×10^4 t.

Due to the influence of reservoir heterogeneity, the wells will see gas quickly and gas channeling and the oil increase effect will be reduced. The appropriate adjustment measures should be taken to gas channeling: when CO_2 is low in the producing well, small fracturing and filling of holes can also be taken to close the gas channeling well near the well. When the CO_2 content of producing wells increases rapidly, the current injection-production relationship should be maintained and the production time should be extended as much as possible. When the production well maintains high content and decreases output, it indicates that it is in a state near gas channeling, and injection and production allocation and intermittent oil production should be carried out to improve formation pressure and restrain the occurrence of gas channeling. When gas channeling occurs, choose to shut down the well group for a long time or alternate water and gas to control gas channeling. After the measures were taken in the field, the effect was satisfactory. The cumulative oil increase was 9.3×10^4 t, the CO_2 oil exchange rate was 0.32 t/t, the gas-oil ratio was reduced from 308 m^3/m^3 to 195 m^3/m^3, and the ultimate oil recovery of the block was increased by 14.6%.[35,36]

2.2.2. The Development Characteristics of Oil Reservoirs under Immiscible Miscible Conditions. 2.2.2.1. The Wei 42 Test Area in Zhongyuan Oilfield Reservoirs. The depth of the test area is 3200−3700 m, the average permeability is 2.25 mD, and the geological characteristics are similar to that of Hu 96 block, but before gas injection, the average water injection pressure is 41 MPa, the comprehensive water content is 74.2%, and the recovery degree is 13.23%. In January 2016, CO_2 flooding was implemented in 6 well groups. After 2 months, the oil increase effect was gradually seen in 11 Wells, the average water cut was reduced by 20%, the peak daily oil increase was 10.6 t/d, the average daily oil increase was 4.5 t/d, and the cumulative oil increase was 1906 t.[37,38]

There is a great difference from the Hu 96 block: the moisture content decreased significantly, and the liquid production remained unchanged or slightly decreased; the fastest oil wells can see obvious results within 2 months, and the water cut is reduced by 30%. Gas channeling is serious, and CO_2 output can be seen in high-position oil wells within 2 months, and the CO_2 content is as high as 90% after 1 year. The gas channeling proportion of low-position oil wells is small, mainly along the direction of fractures and small well spacing, and the CO_2 content is 40%. The reason is the small well spacing, the average well spacing is only 260 m. Oil and water wells are commonly fractured; before gas injection, the formation pressure is 22 MPa

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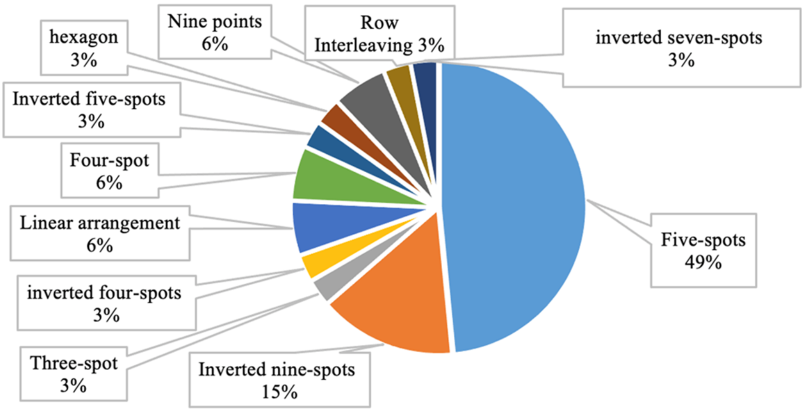

Figure 6. Percentages of different well-patterns of CO_2 flooding at home and abroad.

and MMP is 29.77 MPa. The matrix permeability is low and CO_2 circulates in fractures. The CO_2 content of production wells increases, the pump efficiency decreases, and the liquid production decreases.

To solve this problem, CO_2 flooding parameters were optimized in this block. First, the injection-production well spacing was optimized. All the old injection-production Wells in Block Wei 42 had been fractured, and the average fracture half-length was 60−90 m. Second, the injection parameters are optimized. When the gas injection is 0.35 PV and the optimal gas injection speed is 30−35 t/d, the oil change rate is 0.34 t/t, which can achieve high economic benefit development. Finally, the optimization of the well soaking time can increase the reservoir pressure, reduce the interfacial tension, improve the miscible effect, and expand the macro and micro swept volume, but it will affect the production time rate at the same time. After comprehensive consideration, the optimal soaking time is 1 year. After the implementation, the average daily gas injection per well is 30 t, the cumulative gas injection is 5.40×10^4 t, the comprehensive water cut is reduced by 20%, the peak daily oil increase is 10.6 t, and the cumulative oil increase is 4396 t.[39,40]

2.2.2.2. The Yaoyingtai Oilfield Reservoirs. The main development strata of the Yaoyingtai oilfield are the Qingyi-ii and Qingyi-iv sandstone groups. The medium depth of the reservoir is 2100m, the average porosity is 14.23%, the average permeability is 2.0×10^{-3} μm^2, the delta front sedimentary microfacies, natural microfractures are developed, and the fracture density is about 0.2/m. The crude oil viscosity is 1.91 mPa·s, the crude oil density is 0.79 g/cm^3, the original formation pressure is 22.64 MPa, the average formation pressure before the gas injection is only 12 MPa, and the MMP is 26.3 MPa, which is immiscible flooding.[41,42]

As shown in Figure 5, in the early stage of the oil field, the water cut before gas injection was 82.4%, 12 water injections, and 34 productions were linear displacement along the fracture row pattern, with continuous gas injection first and alternate gas and water injection later. The total amount of injection was 0.8 HCPV. Gas injection began in April 2011, with 6 pumps in the first phase continuous gas injection for 1.5 years, and 6 pumps in the second phase, and gas water injection was implemented alternately with the first phase. The distance between injection and production wells is about 300 m, and the daily injection of a single well is about 30 t. The gas injection was stopped in August 2015. The cumulative gas injection was 22.6×10^4 t, the corresponding 29 wells were effective, and the cumulative oil increase was 1.74×10^4 t, with 1.1% stage extraction and 92.6% stage storage rate.

The permeability anisotropy of the reservoir in the test area is quite different, and the oil wells in the center of the fracture development and hyperpermeability zone see gas quickly and have serious gas breakthroughs earlier. Profile control or plugging measures are carried out in combination with geological analysis when the gas is just seen. Considering the oil displacement efficiency of well groups, Wells with a gas-oil ratio of more than 400 m^3/t and a significant decline in oil production produce intermittently, and well groups with serious gas channeling perform multiple rounds of depth profile control first. If the plugging effect is good, the injection method should be adjusted to periodic water injection according to the timing, but the water injection should not be too large.

In general, both theoretical research and practice show that for a given reservoir, the recovery rate of CO_2 miscible flooding is significantly higher than that of immiscible flooding. The main type of CO_2 flooding in the U.S. is miscible flooding, and the number of miscible flooding projects and EOR production are much higher than immiscible flooding.[43] In 2014, the total number of CO_2 flooding projects was 139, of which the number of miscible flooding projects was 128; the total annual oil production of CO_2 flooding was 13.71 million tons, of which the annual oil production of miscible flooding was 12.64 million tons.[44] The success rate of CO_2 miscible flooding projects is relatively high. Besides, 104 successful projects of CO_2 miscible flooding projects in the U.S., accounting for 81.2%. The successful commercial application of CO_2 flooding technology in the U.S. is inseparable from the support of favorable policies and regulations and the continuous rise in oil prices since 2000.[45] In China, few gas injection projects have completed the full lifecycle, and the gas flooding technology is still in the test and improvement stage. Such as the CO_2 miscible flooding test in the Caoshe oil reservoir, Daqing Zijing oil reservoir, Daqing Haita oil reservoir, Tuhapubei oil reservoir, and Tarim Donghetang natural gas miscible flooding test have obtained good technical results, and the development of miscible flooding is conducive to improving confidence in gas injection and enhanced oil recovery.

Additionally, there is no obvious difference between immiscible flooding and miscible flooding in the actual process, and there is no high requirement in reservoir management and implementation difficulty. It is the basic requirement to choose the reasonable development mode of the oil reservoir according to the possible realistic conditions. The CO_2 flooding types in

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Table 6. Key Indicators of Some Oil Fields in China

blocks	well pattern	injection well count	oil well count	injection pressure (MPa)	daily injection rate (*t*)	injection mode
Hong 87−2	five-spots	1	4	<28	40	continuous injection
Gao 89−4		1	6	<26	40−55	continuous injection
Fang 48	five-spots	14	26	<24	20−50	intermittent injection
Shu101	five-spots	8	14	<25.5	50	intermittent injection
Hei 59	inverted seven-spots	5	19	<40	30−40	first water injection, then continuous injection
Caoshe	point area	5	10		25	continuous injection

Gao 89 of the Shengli oilfield, BD33 of the Yaoyingtai oilfield, Northeast Bureau of Sinopec, and Shu101 and Shu16 of the Daqing oilfield and the Wuqi oilfield, respectively, all belong to immiscible flooding and have achieved different oil increase effects.[46]

According to statistics, there are 40 immiscible CO_2 flooding projects implemented in the world, including 11 projects in the U.S., 1 project in Canada, 5 projects in Trinidad, and 8 projects in China. The global immiscible CO_2 flooding projects range from 4.7% to 12.5%, with an average of 8.0%, and immiscible CO_2 flooding projects in China range from 3.0% to 9.0%, with an average of about 5.5%.

3. DISCUSSION

3.1. Analysis of Field Application CO_2 Flooding Challenges. Through the field application of the CO_2 flooding pilot tests, it can be seen from the results that miscible flooding and near-miscible flooding can achieve better production effects, with a long response period and slow gas breakthrough speed. The effect of CO_2 immiscible flooding is relatively poor, especially in fractured reservoirs, where the gas channeling speed is fast, the swept volume is difficult to expand, and the recovery effect is poor. The injection and production parameters of CO_2 flooding in oil fields have a great influence on the recovery effect. As shown in Figure 6, the empirical range of parameters can be obtained through the statistics of the key indicators of CO_2 flooding field schemes at home and abroad, and the ideal index value can be obtained combined with reservoir characteristics.

(1) Gas injection well pattern: It is mainly five-point (close to 50%). Reservoirs with low dip Angles can follow the injection well pattern, using five-point, antinine-point, and antiseven-point area layouts. In addition, large dip Angle reservoirs use linear row patterns, top injection, and bottom production;[47]

(2) Well spacing and well pattern density: Technical and economic benefits need to be taken into account. At present, 92% of the reservoir well pattern density is (less than 10−70) × 10^4 m^2, and 2/3 is (less than 10−30) × $10^4 m^2$. Foreign reasonable well pattern density (10−40) × $10^4 m^2$, well spacing 200−250 m. The simulated reasonable well distance in the Caoshe oilfield is 300−350 m, limited by the old well pattern, and the actual average is 260 m.

(3) Injection methods: The main injection methods are continuous gas injection, intermittent gas injection, and water gas alternation (WAG), currently more than 80% of foreign WAG, which was first implemented in Canada in 1957, achieving the goal of reducing the total CO_2 demand. The rate of water−air alternation in most foreign countries is constant 1:1, while WAG is used more in medium and high permeability oil fields in China, and continuous or intermittent gas injection is used in low permeability oil reservoirs, which is not conducive to gas channel control.

As shown in Table 6, the domestic Jilin oilfield uses a gradual change: large gas and small water reduce gas and increase water, the gas−water ratio is too large with easy gas channeling, and the effect is too small, generally 1:1 is the best. In addition, WAG in the strong water wet reservoir generally appears water lock phenomenon, injection capacity decreased, pipeline corrosion, and bottom scale, increase the cost, so in the actual site, the early continuous slug flooding is the main, the late WAG is auxiliary.

(4) Injection-production well ratio: The number of injection-production wells used in foreign CO_2 flooding is 1:1.1−1:2.5, as shown in Figure 7, which is also the reason why the five-spot well pattern and inverse nine-point well pattern are commonly used.

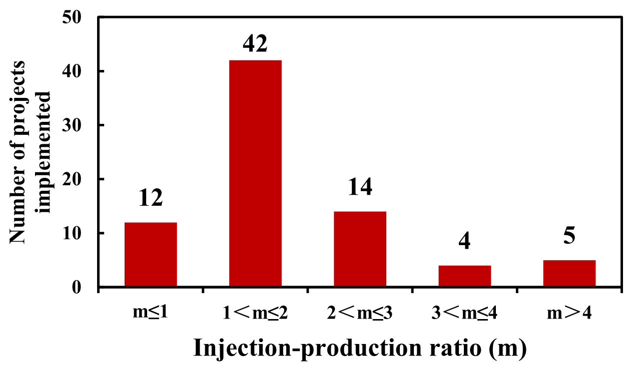

Figure 7. Foreign CO_2 flooding injection-production Wells ratio.

In addition, it is more advantageous to carry out CO_2 flooding when there is a CO_2 gas source near the oil field, which can guarantee a stable supply of gas sources for a long period of time, and the cost is lower. The immiscible oil field should be selected for implementation, the effect and benefit of an immiscible oil field are much worse, and the oil displacement effect of near-miscible and miscible oil reservoirs are close, so experimental exploration can be carried out (Jilin oil field is paying more attention to this at present). In the scheme design, the scale and schedule should be arranged according to the injection-production balance, the well-pattern and injection-production parameters should be optimized by drawing on domestic and foreign experience, the economic and social benefit evaluation should be carried out, and the requirements of well control and Health, Safety, and Environment (HSE) should be put forward.

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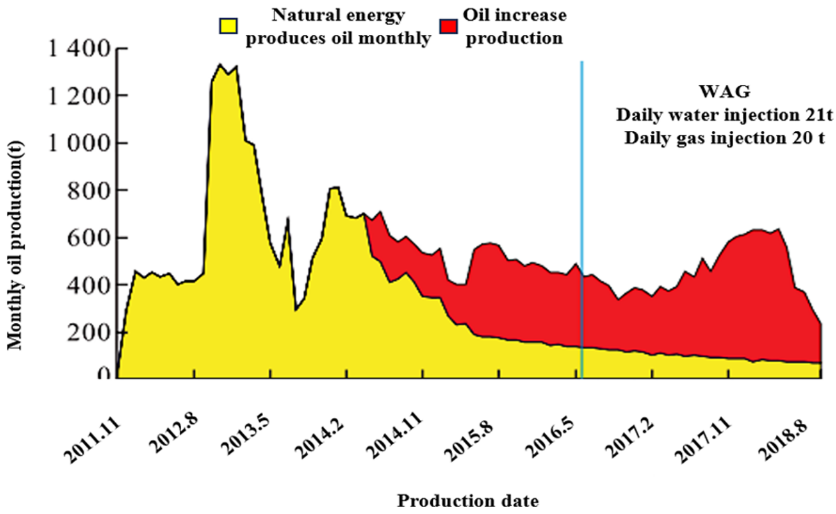

Figure 8. Variation curve of oil production and oil increase in Zhang 3 block of Zhangjiatuan Oilfield, Subei Basin.

Table 7. Summary and Comparison of CO_2 Anticorrosion Technologies

anticorrosion technology		advantage	disadvantage
anticorrosion technology	ordinary carbon steel with corrosion inhibitor	less initial investment	the late process is complex and the effect is general
	cathodic protection	play a certain anticorrosion role	limitations and high construction cost
	inner coat	improve the quality of equipment use	harsh application conditions, easy aging
	corrosion resistant alloy	good anticorrosion effect	first time to invest more

With the gradual deepening of field tests, there will be many mine problems, such as increasing gas content in the production fluid of production wells, resulting in difficulties in lifting and metering, increasing the gas–liquid separation difficulty after increasing the gas production in the gathering and transportation system, and increasing the injection pressure after WAG. Technical solutions should be prepared in advance, and effective CO_2 storage should be carried out while implementing displacement. This has economic benefits, social benefits, and broad application prospects.

3.2. Existing Problems and Solutions. Some problems are inevitable in the process of gas flooding production. There are mainly (1) early gas breakthrough, or fracture channeling; (2) corrosion; and (3) solid phase deposition. The main countermeasures are to avoid early gas breakthroughs and decrease the injection and production rate by changing the well pattern and adjusting the injection and production strategy. Coating an anticorrosive layer or adding a corrosion inhibitor to weaken the corrosion effect, etc. After taking the following corresponding measures, domestic oil fields have achieved good results.

3.2.1. Gas Channeling Prevention. In China, most of the oil reservoirs are continental deposits with serious heterogeneity, which will inevitably affect the swept volume of CO_2. When gas flooding is used to enhance oil recovery, gas channeling is an unavoidable phenomenon, which will seriously affect the production effect. In addition to chemical channeling prevention, injection, and production method optimization is an effective means to prevent channeling and increase CO_2 swept volume, among which water–gas alternations are the best injection methods. From the field implementation situation, due to the difficulty of water injection in low–ultralow permeability reservoirs and the risk of water locking, most test areas adopt the first continuous gas injection method in the test injection stage and the early stage of displacement. With the progress of displacement, it gradually changes to the mode of water–gas alternation.[48−51]

As shown in Figure 8, compared with the changes in production before and after the conversion of water and gas, even if the effect has been achieved before the conversion of WAG and the output has been significantly increased, the effect will still again be achieved after the conversion of water and gas, and the output will appear as the second peak.[52]

In addition, the Changqing Oilfield has established a comprehensive identification standard for gas channeling to form a hierarchical regulation policy for CO_2 flooding in low permeability reservoirs. By determining the corresponding CO_2 content of free gas front breakthrough, the comprehensive identification standard for gas channeling in the test area has been formulated in combination with the economy. Aiming at "maintaining miscible phase, controlling gas channeling, and decreasing decline", the regulation countermeasures of different gas drive stages are formulated. Therefore, it is recommended to implement the water–gas alternations policy in reservoirs that can be flooded or can be flooded after continuous displacement for some time, carry out real-time monitoring at the same time, and take corresponding measures for different gas channeling stages.[53]

3.2.2. Anticorrosion Technology. Under the background of surface and underground integration of oilfield development engineering, compared with traditional oil displacement technology, CO_2 flooding enhanced oil recovery technology exposes some new problems. As shown in Table 7, the corrosion problem of pipelines, gathering facilities, and treatment equipment are the most prominent, and corrosion perforation phenomenon occurs frequently, which directly affects the normal production and operation of oilfield systems.[54,55]

From the current development of relevant technologies in China, the anticorrosion process can be divided into two

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aspects: anticorrosion process control and corrosion-resistant alloy control, which can be seen in the following table.

At present, Changqing Oilfield has completed 10 512 m of tungsten−nickel-coated tubing and 64 000 m of organic-coated anticorrosive tubing in response to the problem of CO_2 flooding corrosion. Among them, the CO_2 pressure of tungsten−nickel coated tubing in the gas channeling well reaches 15 MPa, which remains intact in the environment for 10 months without corrosion. The organic wear-resistant coating anticorrosive tubing showed a bubbling phenomenon when the CO_2 content of the tubing was 296 ppm in the gas well after 9 months in the environment. In addition, the industrial product of integrated corrosion and scale inhibitor was developed, which was applied in 37 Wells with corrosion rate ≤0.076 mm/a, meeting the construction requirements of CO_2 flooding and storage in the Changqing Oilfield.[56,57]

3.2.3. Solid Deposition Control. The organic (asphaltene) precipitate and inorganic precipitate produced in the process of CO_2 flooding will cause serious damage to the porosity and permeability of the reservoir, resulting in increased crude oil flow resistance and reduced oil recovery. For immiscible displacement, considering that the damage degree of reservoir asphaltene and inorganic precipitation to reservoir seepage capacity is relatively small in the process of continuous CO_2 flooding, reservoir damage prevention is mainly implemented in the subsequent WAG flooding process, and chemical reagents are added to form stable metal complexes, thereby reducing inorganic precipitation formed in the process of displacement. For miscible displacement, asphaltene inhibitors are injected near wells to reduce the damage caused by asphaltene precipitation in the displacement process. There is a specific threshold pressure for CO_2 flooding solid phase deposition, and the deposition law presents three trends slow increase, rapid rise, and gradual slowdown. According to the experimental results, it is proposed that the injection pressure level of CO_2 flooding development should be lower than the threshold pressure of solid phase deposition, to effectively inhibit the occurrence of solid phase deposition and reduce the damage degree of CO_2 flooding development solid phase deposition reservoir.[58−63]

Gao 899 block of the Shengli Oilfield was first selected 1.3 times minimum miscible pressure (40.13 MPa) for CO_2 flooding development. After considering the influence of solid phase deposition, it was found that the recovery rate was 16.7% and the solid phase deposition content was 15.8% when maintaining 1.3 MMP development.[64−66] When the pressure is reduced to 1.2 MMP, the recovery rate is unchanged, but the solid phase deposition content is reduced to 5.3%, that is, properly reducing the CO_2 flooding development pressure maintenance level can significantly reduce the degree of solid phase deposition while ensuring the development effect.[67−69]

4. CONCLUSIONS

In this study, several field applications of CO_2 miscible, near-miscible, and immiscible flooding carried out in different oilfields and oil formations are reviewed. The different challenges, especially the ones that are related to the design scheme and operation parameters, are also systematically analyzed where adequate solutions and countermeasures are proposed.

(1) Due to heterogeneity, miscible flooding and near-miscible flooding in different types of reservoirs in China can achieve a better stimulation effect, with a long response period and slow gas breakthrough rate. The effect of CO_2 immiscible flooding is relatively poor, especially in fractured reservoirs, where the gas breakthrough speed is fast and the swept volume is difficult to expand. In addition, it is more advantageous to carry out CO_2 flooding when miscible flooding can be carried out and there is a CO_2 gas source nearby. Possible changes, such as pressure changes and rapid gas detection, should also be considered before development, and plans and HSE scheme design should be made in advance.

(2) In the actual development of the reservoir, technical and economic benefits should be taken into account, and appropriate technical indicators should be selected during CO_2 flooding. Most reservoirs in China and abroad should choose the five-point well pattern, well pattern density (10−40) × $10^4 m^2$, well spacing (200−250m), injection mode is multicontinuous slug flooding in the early stage, supplemented by WAG in the later stage, and the slug ratio is 1:1. The number ratio of injection-production wells is 1:1.1−1:2.5.

(3) When CO_2 flooding is implemented in the field, there are many challenges such as difficult miscibility, high risk of gas channeling, and strong corrosion problems. When gas channeling occurs, in addition to chemical channeling prevention, water−gas alternating is a more effective method. Pipeline coating or replacement materials have a great anticorrosion process. Solid phase deposition is caused by the precipitation of asphaltene in the process of oil displacement. Adding chemical reagents to form metal complexes can inhibit deposition. In addition, properly reducing the pressure to less than the threshold pressure can also effectively inhibit the occurrence of deposition.

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Notes

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■ REFERENCES

(1) Li, Y.; Huang, W. H.; Jin, Y.; He, Y. F.; Chen, Z. H.; Tang, Y.; Wu, G. Y. Different reservoir types of CO_2 flooding in Sinopec EOR technology development and application under dual carbon vision. *Petroleum Reservoir Evaluation and Development* **2021**, *11* (06), 793−804.

(2) Mohan, H.; Carolus, M.; Biglarbigi, K. The potential for additional carbon dioxide flooding projects in the United States. In the SPE Symposium on Improved Oil Recovery: Tulsa, OK, 2008.

(3) Qin, J. S.; Han, H. S.; Liu, X. L. Application and enlightenment of carbon dioxide flooding in the United States of America. *Petroleum Exploration and Development* **2015**, *42* (2), 232−240.

(4) Jia, K. F.; Ji, D. C.; Gao, J. D.; Wang, S. L. The existing state of enhanced oil recovery by CO_2 flooding in low permeability reservoirs. *Unconventional Oil Gas* **2019**, *6* (1), 107−114.

(5) Li, S. L.; Guo, P.; Dai, L.; Sun, L. Strengthen gas injection for enhance oil recovery. *Journal of Southwest Petroleum Institute* **2000**, *22* (3), 41−46.

(6) Liu, X. B. Application and evaluation of CO_2 miscible flooding in extra-low permeability beach-bar sand reservoirs. *Petroleum Geology and Recovery Efficiency* **2020**, *27* (03), 113−119.

(7) Jiang, H. Y.; Shen, P. P.; Chen, L. D. The study on situation of CO_2-EOR of north America industry. *Energy China* **2007**, *29* (7), 30−34.

(8) Jiang, H. Y.; Shen, P. P.; Lu, Y. The situation of enhance worldwide oil and gas resource recovery using CO_2. *Special Oil Gas Res.* **2010**, *17* (2), 5−10.

(9) Jablonowski, C.; Singh, A. A survey of CO_2-EOR and CO_2 storage project costs. In the SPE International Conference on CO_2 Capture, Storage, and Utilization: New Orleans, LA, 2010.

(10) Koottungal, L. 2014 worldwide EOR survey. *Oil Gas J.* **2014**, *112* (4), 41−91.

(11) Long, M.; Qi, M.; Feng, C. L. Research progress of miscible and immiscible carbon dioxide flooding. *Sino-Global Energy* **2018**, *23* (02), 18−26.

(12) Zhang, J. C.; Sun, L. Y.; Bai, Z. W. A comparative study of offshore and onshore oilfield development models. In The 7th National Fluid Mechanics Academic Conference: Taiyuan, China, 2012.

(13) Qin, J. S.; Han, H. S.; Liu, X. L. Application and enlightenment of carbon dioxide flooding in the United States of America[J]. *Petroleum Exploration and Development* **2015**, *42* (2), 232−240.

(14) Hu, Y. L.; Hao, M. Q. Development characteristics and cost analysis of CCUS in China[J]. *Reservoir Evaluation and Development* **2020**, *10* (3), 15−22.

(15) Li, Y.; Huang, W. H.; Jin, Y.; He, Y. F.; Chen, Z. H.; Tang, Y.; Wu, G. Y. Different reservoir types of CO_2 flooding in Sinopec EOR technology development and application under ″dual carbon″ vision [J]. *Reservoir Evaluation and Development* **2021**, *11* (6), 793−804.

(16) Liu, X. L.; Chen, H.; Chen, Z. H.; Yang, R.; Song, L. Y.; Bai, M. M.; Qiu, P.; Zuo, M. M.; Li, B. R.; Yang, B. X.; et al. Study on characterization and distribution of four regions of tight sandstone condensate gas reservoirs in the depletion development process[J]. *Fuel* **2024**, *358*, 130267.

(17) Chen, H.; Liu, X. L.; Zhang, C.; Tan, X. H.; Yang, R.; Yang, S. L.; Yang, J. Effects of miscible degree and pore scale on seepage characteristics of unconventional reservoirs fluids due to supercritical CO_2 injection[J]. *Energy* **2022**, *239*, 122287.

(18) Jiang, H. F.; Lei, Y. Z.; Xiong, X.; Yan, L. P.; Pi, W. F.; Li, X. J.; Yu, C. H. An CO_2 Immiscible Displacement Experimental Study Aiming at Fuyang Extra-low Permeability Layer at Peripheral of Daqing Placanticline. *Geoscience* **2008**, No. 04, 659−663.

(19) Liu, W.; Pan, J. M. Study on development stage of Chujialou oilfield. *Mineral. Petrol. (Vienna, Austria)* **1999**, No. 02, 66−69.

(20) Liu, B. G.; Zhu, P.; Yong, Z. Q.; Lv, L. H. Pilot test on miscible CO_2 flooding in jiangsu oil field. *Acta Petroleum Sinica* **2002**, No. 04, 56−60.

(21) Lou, Y.; Yang, S L.; Zhang, X.; Yu, Y.; Yin, D. D.; Li, M.; Wen, B. Experimental research on CO_2 miscible flooding by advanced gas injection in low permeability reservoir-case of H79 block, Jilin oilfield. *Petroleum Geology and Recovery Efficiency* **2012**, *19* (05), 78−80.

(22) Qian, W. M.; Zhang, F. D.; Zhang, J. R.; Meng, C. R. Field test and effectiveness evaluation of CO_2 immiscible displacement in Chujialou oilfield. *Special Oil Gas Res.* **2001**, No. 04, 79−82.

(23) Li, M. P.; Li, Y J.; Yang, J F.; Yang, F T.; Yan, M.; Tao, T.; Zhao, Y Y. Research and field test of CO_2 flooding technology in Huang3 Zone. *Petrochemical Industry Application* **2020**, *39* (05), 71−75.

(24) Zhang, F. D.; Wang, Z. L. The filed experiment and results analysis of CO_2 miscible displacement in Caoshe oil filed of the north Jiangsu basin. *Petroleum Geology Experiment* **2010**, *32* (03), 296−300.

(25) Guo, D. B.; Xu, H. M. Laboratory experiments of CO_2 flooding in deep-buried high-pressure low-permeability reservoirs: A case study of block Hu96 in Zhongyuan Oilfield. *Petroleum Geology Experiment* **2014**, *6* (01), 102−105.

(26) Sun, T. Y. Pilot test on CO_2 flooding of low permeability oil reservoir in Dongpu sag. *Petrochemical Industry Application* **2021**, *40* (04), 28−30.

(27) Li, Y.; Zhou, D.; Wang, W.; Jiang, T. X.; Xue, Z. J. Development of unconventional gas and technologies adopted in China. *Energy Geosci* **2020**, *1* (1−2), 55−68.

(28) Mahmud, H. B.; Bin Muhammad Hisham, M. H.; Mahmud, W. M.; Leong, V. H.; Shafiq, M. U. Petrophysical interpretations of subsurface stratigraphic correlations, Baram Delta, Sarawak, Malaysia. *Energy Geosci.* **2020**, *1* (3−4), 100−114.

(29) He, J. C.; Liao, G. Z.; Wang, Z. M. Oilfield development strategy and replacement techniques[J]. *Acta Petrolei Sinica* **2012**, *33* (3), 519−525.

(30) Guo, P.; Xu, Y.; Niu, B. L.; Zhang, Y.; Li, T. The mechanism of quasi-miscible CO_2 flooding in Block G89 low permeability reservoir of Shengli oilfield. *Special Oil Gas Res.* **2012**, *19* (02), 104−106.

(31) Han, X. Corrosion analysis and control of CO_2 flooding ground production system in Gao 89 block. *Oil-Gas Field Surface Eng.* **2012**, *31* (11), 11−13.

(32) Li, C. Q. Application of CO_2 miscible flooding technology in the development of ultra-low permeability reservoir in Block Gao 89−1. *J. Oil Gas Technol.* **2011**, *33* (06), 328−329.

(33) Li, J. M. Pilot test of enhanced oil recovery by CO_2 flooding in ultra-low permeability reservoir in block Gao 89−1. *Inner Mongolia Petrochemical Industry* **2012**, *38* (05), 127−129.

(34) Yang, Y.; Cao, X. P.; Han, W. C.; Zhang, D.; Zhang, Q. Y.; Wang, Y.X. Non-linear flow laws of CO_2 flooding in ultra-low permeability reservoirs in Gao89 area of Shengli Oilfield. *Petroleum Geology and Recovery Efficiency* **2022**, *30* (02), 36−43.

(35) He, H. F.; Hu, X. H.; Zhuang, Y. H.; Liu, P. C.; Ma, Y. N.; Wu, W.; Han, Y.; Fang, Y. Study and application of injection-production parameter optimization for CO_2 flooding in low-permeability reservoirs: A case study of Block A in Shengli Oilfield. *Petroleum Geology and Recovery Efficiency* **2023**, *30* (02), 112−121.

(36) Zhang, X. M.; Xue, J. F. Study on enhanced oil recovery technology of CO_2 flooding in Gao 89−1 block. *Nei Jiang Sci. Technol.* **2012**, *33* (07), 98.

(37) Ding, Y. Technology and application of CO_2 flooding in low-permeability and high-pressure water injection reservoirs in Pucheng oilfield. *Petroleum Geology and Engineering* **2019**, *33* (06), 73−76.

(38) Zhu, W. Evaluation and development technology application of difficult-to-use reserves in Wei 42 block reservoir. *Inner Mongolia Petrochemical Industry* **2007**, No. 05, 232−234.

(39) Nie, F. J.; Mao, H. C.; Wang, Q.; Ding, Y. CO_2 flooding for enhanced oil recovery technology and field practice in Zhongyuan Oilfield. *Petroleum Geology and Recovery Efficiency* **2020**, *27* (01), 146−151.

(40) Wang, H. G.; Sheng, J. M.; Han, M. S.; Guo, Y. S.; Zhao, H.; Du, Y. X. Overall reconstruction of low porosity and low permeability reservoir in block Wei 42−43 of Pucheng Oilfield. *J. Oil Gas Technol.* **2005**, No. S3, 116−117.

(41) Dong, C. R.; Gao, Z. H.; Li, X. Pilot test of CO_2 flooding in Yaoyingtai Oilfield. *Liaoning Chemical Industry* **2018**, *47* (06), 578−579.

(42) Wang, J. B.; Gao, Y. C.; Wang, K. Z. Law of gas breakthrough on CO_2 flooding well in ultra-lower permeability reservoir of Yao Yingtai Oilfield. *Fault-Block Oil Gas Field* **2013**, *20* (01), 118−122.

(43) Qin, J. S.; Li, Y. L.; Wu, D. B.; Weng, H.; Wang, G. F. CCUS global progress and China's policy suggestions. *Editorial Department of Petroleum Geology and Recovery Efficiency* **2020**, *27* (1), 20−28.

(44) Wang, G. F.; Yao, J.; Wang, H.; Yu, W. L.; Luo, W. L. Prediction of produced GOR of miscible gas flooding in low permeable reservoirs [J]. *Reservoir Evaluation and Development* **2019**, *9* (3), 14−18.

(45) Li, C. L. Gas channeling influencing factors and patterns of CO_2-flooding in ultra-low permeability oil reservoir[J]. *Special Oil Gas Reservoirs* **2018**, *25* (3), 82−86.

(46) Zhang, N.; Wei, M. Z.; Bai, B. J. Comprehensive review of worldwide CO_2 immiscible flooding [C]. SPE Improved Oil Recovery Conference: Tulsa, OK, 2014.

(47) Yu, K.; Liu, W.; Chen, Z. H. CO_2 miscible flooding technology for continental low permeability reservoir. China Petrochemical Press: Beijing, 2015.

(48) Kane, A. V. Performance review of large-scale CO_2-WAG enhanced recovery project, SACROC unit, Kelly-Snyder field. *J. Petroleum Technol.* **1979**, *31* (2), 217−231.

(49) Ding, W. Analysis on the technology of improving recovery efficiency of low permeability fractured reservoir by alternate injection of water and gas. *China Petroleum and Chemical Standard and Quality* **2014**, *34* (02), 178.

(50) Li, M.; Guan, H.; Hu, S. Y.; Wang, X.; Li, Q.; Yuan, S. M. Optimization of water gas alternate injection production parameters for miscible and immiscible CO_2 flooding in ultra-low permeability reservoir. *Unconventional Oil Gas* **2021**, *8* (01), 60−66.

(51) Meng, F. K.; Su, Y. L.; He, D. B.; Tong, G. Study on injectivity of CO_2 Water-alternating-gas Flooding in Low Permeability Reservoirs. In 2018 International Field Exploration and Development Conference: Xian, China, 2018.

(52) Wang, S. T.; Ma, G. W.; Lang, Q. L.; Yang, T. Y. Study on formation mechanism and prevention technology of gas channeling by CO_2 flooding in low permeability fractured reservoirs. *Energy Chemical Industry* **2022**, *43* (03), 29−34.

(53) Zhang, H. L. Practice and understanding of enhancing the oil recovery by CO_2 miscible flooding. *Petroleum Geology Oilfield Development in Daqing* **2020**, *39* (02), 114−119.

(54) Jiao, Y. H. Discussion on optimization of anticorrosion technology of CO_2 flooding oil and gas Wells. *Chemical Engineering Management* **2015**, No. 14, 177.

(55) Pu, Yu.; Ma, X. Y.; Shi, P. F.; Zou, S. J.; Xue, Z. H.; Zhao, M. Analysis on the application status of anti-corrosion measures in domestic CO_2 flooding field. *China Plant Engineering* **2022**, No. 08, 5−7.

(56) Bai, Y. H. Research & Application of supporting technology for EOR with non-miscible flood of gas injection in block WEN 5. *Drilling Production Technol.* **2008**, No. 02, 68−70.

(57) Lin, G. F.; Bai, Z. Q. Corrosion protection and comprehensive utilization of CO_2 in oilfield. In Proceedings of the Symposium on Carbon Dioxide Emission Control Technology and Resource Utilization: Qingdao, Shandong, 2009.

(58) Guo, Y. W.; Yan, F. P.; Wang, J.; Zhu, H. L.; Yang, J. L.; Chen, Y. C.; Zhang, X. Y. Characteristics of solid deposition and reservoir damage of CO_2 flooding in tight sandstone reservoirs. *Lithologic Reservoirs* **2021**, *33* (03), 153−161.

(59) Guo, M. L.; Huang, C. X.; Dong, X. G.; Zhou, Y.; Tang, R. J. CO_2 EOR mechanism of tight sandstone reservoir in Yanchang oilfield. *Chem. Eng. of Oil Gas* **2018**, *47* (02), 75−79.

(60) Langston, M. V.; Hoadley, S. F.; Young, D. N. Definitive CO_2 flooding response in the SACROC unit. In the SPE Enhanced Oil Recovery Symposium: Tulsa, OK, 1988.

(61) Li, Y. Technical advancement and prospect for CO_2 flooding enhanced oil recovery in low permeability. *Petroleum Geology and Recovery Efficiency* **2020**, *27* (1), 1−10.

(62) Qi, C. M.; Li, R. D.; Zhu, S. D.; Liu, L. H.; Li, J. L. Pilot test on CO_2 flooding of Chang 4 + 51 oil reservoir in Yougou region of the Ordos Basin. *Oil Drilling Production Technol.* **2019**, *241* (02), 249−253.

(63) Qin, J. S.; Li, Y. L.; Wu, D. B.; Weng, H.; Wang, G. F. CCUS global progress and China's policy suggestions. *Petroleum Geology and Recovery Efficiency* **2020**, *27* (01), 20−28.

(64) Stalkup, F. I. Oilfield development by miscible flooding. Petroleum Industry Press: Beijing, 1989.

(65) Sandrea, R.; Dharod, D. Approach screens reservoir candi-dates for EOR. *Oil Gas J.* **2016**, *114* (4), 48−51.

(66) Han, W. S.; McPherson, B. J.; Lichtner, P. C.; Wang, F. P. Evaluation of trapping mechanisms in geologic CO_2 sequestration: Case study of SACROC northern platform, a 35-year CO_2 injection site. *Am. J. Sci.* **2010**, *310* (4), 282−324.

(67) Wang, L. M.; Ye, Y. H.; Dong, X. J. Analysis of current technology of gas injection to enhance oil recovery. *China Petrochem* **2017**, No. 11, 60−61.

(68) Wang, H. M. Adaptive analysis of CO_2 flooding technology and its application in different types of reservoirs. *Petroleum Geology Engineering* **2018**, *32* (5), 63−65.

(69) Xie, S. X.; Han, P. H.; Qian, Y. Pilot field test study on CO_2 flooding in transition zone of eastern Sanan in Daqing Oilfield. *Petroleum Geology and Recovery Efficiency* **1997**, No. 03, 20−26.

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