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Study on the Miscible Behavior of CO_2 Flooding with Different Water Saturation in Low-Permeability Reservoirs#

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ABSTRACT

Injecting CO_2 into low-permeability reservoirs can synergistically enhance oil recovery while achieving carbon storage goals. The miscibility between CO_2 and crude oil during displacement is influenced by pore scale and water saturation. To elucidate the characteristics of various miscibility types in CO_2 flooding at different water saturation within the low-permeability reservoirs of Block H in the JY Oilfield, and to guide the design and optimization of CO_2-EOR schemes, we conducted CO_2-crude oil phase behavior experiments. We established a compositional model for CO_2 flooding numerical simulations in low-permeability reservoirs and proposed standards and methods for classifying multiple CO_2-crude oil miscibility states under different water saturation conditions. Additionally, we determined the influence of gas injection parameters on miscibility state transitions. The results indicate that Block H in the JY Oilfield contains medium-light crude oil with a saturation pressure of 4.762 *MPa* and a minimum miscibility pressure of 17.26 *MPa*. Under varying water saturations, four distinct CO_2-crude oil miscibility states exist. As water saturation increases, the miscibility pressure threshold rises, leading to a decrease in oil recovery. Pore size and residual water significantly impact the miscibility state, with higher water saturation reducing the effectiveness of CO_2 in improving crude oil mobility. Increasing the number of pore volumes injected and using high-purity CO_2 favor achieving miscible and full miscible flooding, resulting in higher displacement efficiency and increased ultimate recovery. The study concludes that CO_2-EOR scheme design for low-permeability reservoirs should prioritize blocks with low to medium water saturation and optimize injection and production parameters based on reservoir structure characteristics. For blocks with higher water saturation, employing near-miscible to miscible flooding at lower pressures can significantly reduce development costs while maximizing economic benefits.

Keywords: CCUS-EOR, miscibility state, enhanced oil recovery, low-permeability reservoirs, water saturation, oil mobility

NONMENCLATURE

Abbreviations	
CCUS-EOR	Carbon Capture, Utilization and Storage-Enhanced Oil Recovery
MDE	Multiple Degassing Experiment
CCE	Constant Composition Expansion Experiment
GOR	Gas-to-Oil Ratio
OVF	Oil Volume Factor
GVF	Gas Volume Factor
ORV	Oil Relative Volume
IFT	Interfacial Tension
Sat.P	Saturation Pressure
VEF	Volume Expansion Factor
Immis.	Immiscible
Near-mis.	Near-Miscible
Mis.	Miscible
Full-mis.	Full Miscible
Sw	Water saturation
PV	Pore volume
Symbols	
σ	Interfacial tension
P	Pressure

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μ	Viscosity
n	Year

1. INTRODUCTION

China's low-permeability and tight oil reservoirs have been found to hold abundant proven reserves and are gradually becoming major development targets[1]. However, after years of water flooding, many of these reservoirs have entered medium to high water-cut stages, leading to challenges such as water injection difficulties and low production rates[2]. Thus, there is an urgent need to develop effective enhanced oil recovery (EOR) technologies. In September 2020, China announced its carbon neutrality and peak carbon goals, ushering in a golden period for the development of Carbon Capture, Utilization, and Storage (CCUS) technologies[3-4]. CO_2 injection in low-permeability reservoirs is a proven EOR technology[5-7] and an effective method for CO_2 sequestration[8]. Consequently, CCUS-EOR is becoming the most popular EOR technology in the petroleum industry[6,9].

Since the proposal of CO_2-EOR, extensive research and experiments have been conducted both domestically and internationally[10]. Traditionally, the miscibility state of CO_2 and crude oil has been categorized into immiscible and miscible states[11], with the capillary tube method[12] being the most commonly used determination method[13]. However, as research and experiments have progressed, the limitations of traditional capillary tube experiments in practical applications have become evident. Orr found that the recovery curve in capillary tube experiments does not show a sudden change but rather exists in a near-miscible state[14]. Subsequently, many scholars have confirmed the existence of near-miscible flooding through theoretical calculations and laboratory experiments[15-16]. However, there are disagreements regarding the regional division of different miscibility states of oil and gas. Traditional methods consider the interfacial tension between oil and gas to be zero in the miscible state[17], with lower recovery in the immiscible state. For near-miscible states, some researchers use 0.8 to 0.83 times the minimum miscibility pressure[18] or interfacial tension less than 0.5 mN/m[19] as the criteria, but these criteria are relatively simplistic and based on experimental or empirical methods. Mu categorized the miscibility states into immiscible, near-miscible, miscible, and full miscible based on oil recovery and critical interfacial tension[20], but did not provide specific classification standards, nor did they consider the impact of varying water saturations on these classifications. Addressing this issue is crucial for understanding the effects of three-phase oil, gas, and water flow on CO_2 miscibility states in low-permeability reservoirs. Currently, the methods for characterizing CO_2 miscibility states in EOR primarily include experimental research and numerical simulation. In experimental research, the minimum miscibility pressure results are compared with reservoir pressure to characterize the miscibility state. However, due to CO_2's extraction effect on crude oil[21] and the non-uniform pressure distribution between injection and production wells[22], the minimum miscibility pressure shows temporal dynamic changes, making this characterization method less accurate. In numerical simulation, Ji[12], Wu[23], and Wang[24] proposed parameters such as the miscible volume coefficient, miscibility coefficient, and miscibility degree to characterize the proportions of different miscibility states. These methods use numerical simulation results to statistically represent the miscibility state, reflecting the dynamic development process of the reservoir. However, CO_2 flooding in low-permeability reservoirs often follows water flooding to enhance oil recovery, involving a three-phase coexistence of oil, gas, and water. Miscibility states are influenced by multiple factors such as pore size effects and water saturation[10]. The aforementioned methods cannot precisely characterize the typical features of different CO_2-crude oil miscibility states or reflect the differential impacts of various microscopic mechanisms on miscibility states.

Therefore, this study conducts CO_2-crude oil phase behavior experiments based on Block H in the JY Oilfield, establishes a compositional model for numerical simulation in low-permeability reservoirs, proposes classification standards and characterization methods for multiple types of CO_2-crude oil miscibility states under different water saturations, and uses field numerical simulations to guide the formulation of enhanced oil recovery schemes and optimization of development parameters.

2. MATERIAL AND FLUID EXPERIMENTAL

2.1 Experimental material

The fluid samples used in this study were obtained from Block H of the low permeability reservoir in the JY Oilfield, where crude oil and associated gas were taken from the same production well. Under reservoir conditions (temperature 90.76 *℃*, pressure 23.0 *MPa*), the crude oil viscosity was 2.25 *mPa·s*, density was 767.7 kg/m^3, saturation pressure was 4.76 *MPa*, and the initial solution gas-oil ratio was 26.58 m^3/m^3, classifying it as medium-light crude oil. The crude oil was flash-separated under surface conditions, and the composition of the well stream was determined using gas chromatography. The specific components are shown in Figure 1.

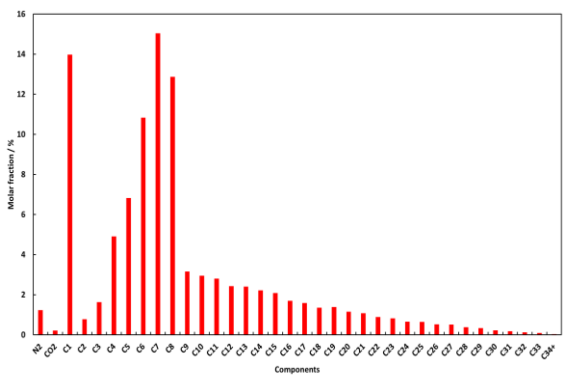

Fig. 1 Composition of fluid in the test area wells

2.2 Fluid properties test experiments

The phase behavior characteristics of underground crude oil and the interaction between CO_2 and crude oil were studied through multiple degassing, constant composition expansion, CO_2 injection expansion, and crude oil viscosity tests. Using site-degassed crude oil and associated gas at reservoir temperature and pressure conditions, an experimental simulated crude oil with dissolved gas was prepared in a PVT reactor according to the target gas-oil ratio (26.58 m^3/m^3), resulting in an actual gas-oil ratio of 28.615 m^3/m^3, which meets the experimental requirements. The experimental setup consisted of a visual PVT cell with a maximum volume of 400 *mL*, with the experimental temperature set to the reservoir temperature. Experimental pressures and results are presented in Tables 1 and 2.

As shown in Table 1, during multiple degassing experiments, the crude oil began to degas, and the solution gas-oil ratio decreased, with the saturation pressure measured at 4.762 *MPa*. The constant composition expansion experiment measured the relative volume of crude oil to be 1.00 at this pressure. Table 2 presents the results of the CO_2 injection PVT experiments. Due to the dissolution and extraction effects of CO_2 in the crude oil, the crude oil viscosity decreased by 30% after CO_2 injection, while the solution gas-oil ratio, saturation pressure, and volume expansion coefficient all increased.

2.3 CO_2 slim tube experiments

The slim tube experiments used the experimental simulated crude oil with dissolved gas. The experimental temperature was set to the reservoir temperature. Four pressure points were tested, and oil recovery at different pressures are shown in Figure 2. The slim tube parameters were: length 20.0 *m*, inner diameter 4.0 *mm*, porosity 36.36*%*, and gas-measured permeability 3986 × 10^{-3} μm^2.

As shown in Figure 2, oil recovery increased progressively with the increase in CO_2 injection pressure. Through linear regression, the minimum miscibility pressure (MMP) of CO_2 and crude oil at reservoir temperature was determined to be 17.26 *MPa*, at which the recovery was 91.4*%*.

Tab. 1 Results of conventional PVT experiments

P *MPa*	MDE GOR $m^3 \cdot m^{-3}$	MDE OVF	MDE GVF	CCE ORV
23.475	28.615	1.087		0.9772
4.762	28.615	1.131		1.0000
3.372	16.7	1.111	0.0324	1.1375
2.592	12.9	1.100	0.0432	1.2643
1.785	8.7	1.088	0.0631	1.6144
1.200	5.5	1.078	0.0778	1.9198
0.860	3.4	1.071	0.1146	2.2193

Tab. 2 Changes of crude oil properties before and after CO_2 injection

CO_2-Oil Viscosity Test				CO_2 Injection Expansion Experiment			
P *MPa*	μ *mPa·s*	P *MPa*	μ *mPa·s*	CO_2 *mol%*	GOR $m^3 \cdot m^{-3}$	Sat. P *MPa*	VEF
23.00	0.8372	12.01	0.688	0	23.9	4.762	1.0000
20.05	0.8069	10.02	0.6573	22.9	27.3	7.323	1.0819
18.02	0.7693	8.07	0.6355	40.9	48.8	9.058	1.1503
16.04	0.7484	6.04	0.6088				
14.05	0.7134	4.98	0.585				

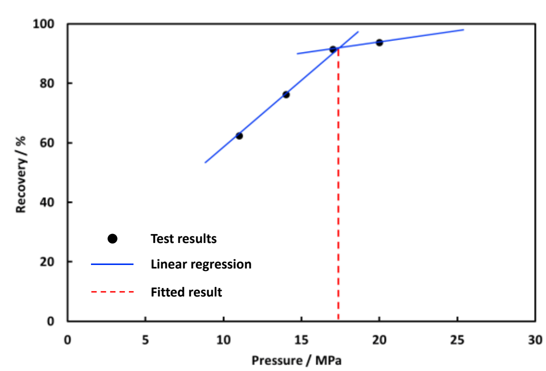

Fig. 2 Minimum miscible pressure test results of slim tube experiments

3. MISCIBILITY STATE CLASSIFICATION AND CHARACTERIZATION

3.1 Numerical experiments

Based on PVT and slim tube experimental data, the pseudo-components were divided, as shown in Table 3. Then the state equation parameters were fitted, and a phase behavior model for the CO_2 containing system was established. Based on the actual slim tube geometric dimensions and fluid properties, a one-dimensional numerical slim tube displacement model was created[25], as shown in Figure 3.

Tab. 3 Pseudo-component Division

Pseudo composition		Number of component
Component	Mole Fraction / *%*	
N2	1.23	1
CO2	0.22	2
C1	13.97	3
C2—C6	24.98	4
C7—C10	34.00	5
C11—C15	11.95	6
C16—C21	8.24	7
C22+	5.41	8

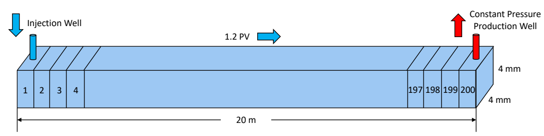

Fig. 3 Model of numerical slim tube experiment

To further study the miscibility state of CO_2 and crude oil under continuous contact in porous media, a numerical experimental method was used to calculate oil recovery at various pressures after injecting 1.2 PV of CO_2 at reservoir temperature[26]. The results are shown in Figure 4. The simulated minimum miscibility pressure (MMP) was found to be 17.28 *MPa*, with a discrepancy of only 0.11*%* compared to the experimental result.

Figure 4 shows that the oil recovery transitions gradually between immiscible and miscible states, indicating a near-miscible region. Thus, the experimentally determined MMP does not strictly achieve miscibility in the physical and chemical sense but rather represents a near-miscible state.

3.2 Miscible state division

Due to the large pores and unstable sand-filled structure of the slim tube experimental setup, it cannot accurately represent the pore structure characteristics of low-permeability reservoirs. Additionally, the experimental fluid was a reconstituted crude oil with gas, excluding formation water, leading to significant discrepancies between the MMP in actual reservoir displacement processes and slim tube experiments [15,27-28]. Considering these factors, a numerical simulation compositional model was established using laboratory parameters such as a target reservoir porosity of 12.5*%* and an average permeability of 11.4 *mD*. This model was used to determine the MMP and interfacial tension for CO_2 and crude oil under low water saturation in low-permeability reservoirs.

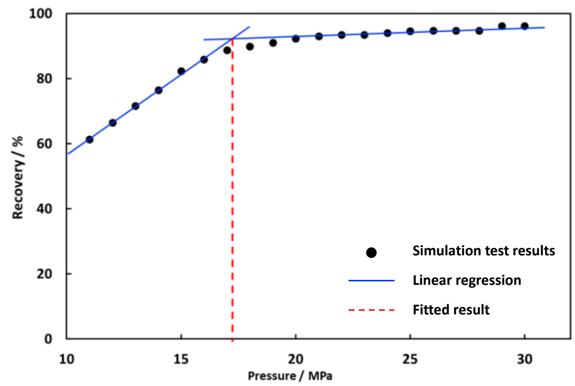

Fig. 4 Simulation results of minimum miscible pressure in numerical slim tube experiments

Figure 5 shows the oil recovery and interfacial tension curves for different water saturations in low-permeability reservoirs after injecting 1.2 PV of CO_2. Based on the trends in oil recovery and interfacial tension, the miscibility states were classified into immiscible, near-miscible, miscible, and full miscible states. At low water saturation, the CO_2-crude oil miscibility state is mainly influenced by the pore size effect, resulting in a lower MMP[29]. The oil recovery shows a continuous gradient trend, with a smaller near-miscible range, and can achieve miscible and full miscible states. As water saturation increases, the shielding effect of residual water on the miscibility state becomes more significant, hindering CO_2-crude oil contact[22,30]. The interfacial tension at the displacement front increases, expanding the immiscible and near-miscible regions while reducing the miscible and full miscible regions, ultimately decreasing oil recovery. Table 4 provides the classification criteria and pressure boundaries. This classification method effectively assesses the impacts of pore size effect and residual water shielding effect,

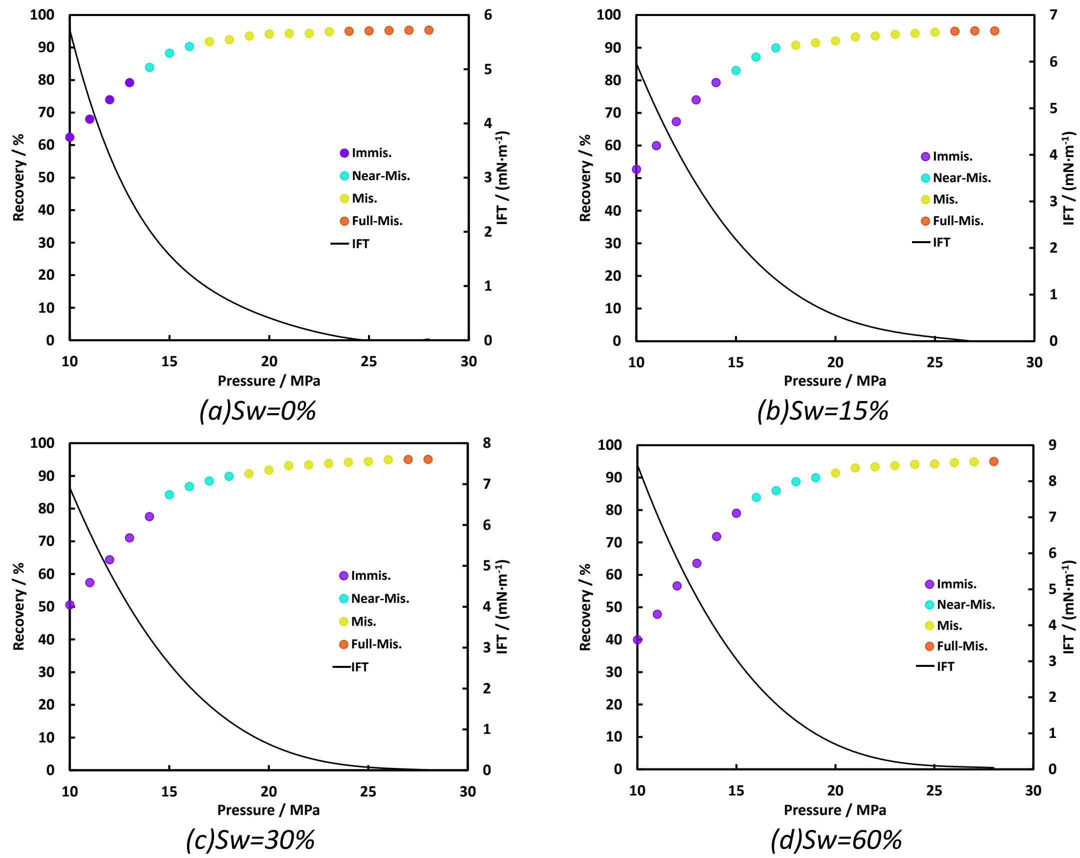

Fig. 5 Simulation results of in numerical slim tube experiments with different water cut in low permeability reservoir

Tab. 4 Different miscible states division

Miscibility State	Water Cut / %	Pressure Range / MPa
Immis.	0	$P \leqslant 13$
	15	$P \leqslant 14$
	30	$P \leqslant 14$
	60	$P \leqslant 15$
Near-Mis.	0	$13 < P \leqslant 16$
	15	$14 < P \leqslant 17$
	30	$14 < P \leqslant 18$
	60	$15 < P \leqslant 19$
Mis.	0	$16 < P \leqslant 23$
	15	$17 < P \leqslant 25$
	30	$18 < P \leqslant 26$
	60	$19 < P \leqslant 27$
Full-Mis.	0	$P > 23$
	15	$P > 25$
	30	$P > 26$
	60	$P > 27$

guiding the formulation and implementation of enhanced oil recovery measures.

3.3 Characterization methods

To quantitatively characterize the displacement effects of different miscibility states during CO_2 flooding, previous studies have defined concepts such as miscibility volume coefficient or miscibility coefficient. These are primarily used to describe the proportions of different miscibility states by statistically counting grid numbers from numerical simulation results[12,23-24]. However, in the development of CO_2 injection in low-permeability reservoirs with medium to high water saturation, the pore size effect and residual water shielding effect present different impacts on the CO_2-oil miscibility state[31]. The aforementioned methods cannot accurately describe the main factors influencing CO_2 flooding efficiency. Therefore, building upon prior research, a three-dimensional compositional simulation model was established. Combined with experimental and miscibility state classification results, the flow coefficient (Kh/μ) was used to characterize the variation patterns and main controlling factors of multiple miscibility states of CO_2 flooding at different water saturation stages in low-permeability reservoirs.

As shown in Figure 6, when the water saturation is low, the pore size effect enhances the miscibility between oil and gas, improving the flow capacity of crude oil. However, as the water saturation increases, the contact mode between CO_2 and crude oil changes[22], weakening the improvement effect on crude oil flow capacity. In the immiscible displacement stage, CO_2 only plays a role in dissolution and convection, and the improvement in crude oil flow capacity is not significant, with residual water shielding being the dominant factor. As the pressure increases, CO_2 preferentially bypasses residual water along the wall exceeding the main streamline direction[5], and the pore size effect promotes forward contact. However, the shielding effect hinders backward contact, achieving near-miscible displacement with some improvement in crude oil flow capacity. When the pressure is higher, the pore size effect enhances both forward and backward contact, fully leveraging the dissolution and diffusion effects of CO_2, causing crude oil volume expansion to displace residual water[32]. The amount of CO_2 bypassing residual water increases, forming breakthrough channels, reducing the shielding effect, and resulting in weak two-phase displacement with increased displacement efficiency and significant improvement in crude oil flow capacity. As the pressure further increases, the mass transfer capacity of CO_2 is enhanced. However, under the coupled influence of pore size effect and residual water shielding effect, the oil-gas interfacial tension becomes unstable[31], with the improvement in crude oil flow capacity being slightly greater than that in the miscible state

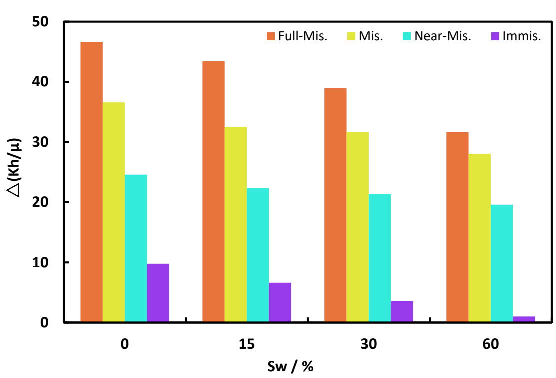

Fig. 6 Comparison chart of the improvement effects of different miscible states on flow coefficients

3.4 Influencing factors

In the actual development of reservoirs, various complex factors influence the pore size effect and residual water shielding effect, thereby affecting the oil-gas miscibility state. Considering the large pore volume (PV) injection and the mixing of impurity gases during subsequent CO_2 reinjection, factors such as the number of CO_2 injection PVs and the impurity gas content in the injected gas were selected for study. The miscibility states of CO_2 and crude oil under different factors are shown in Table 5.

When the number of injected PVs increases, the amount of CO_2 injected within the same time increases, raising the reservoir pressure. The proportions of immiscible and near-miscible states decrease, while the proportions of miscible and full miscible states increase, resulting in a 1.77% increase in oil recovery. When impurity gases such as nitrogen or methane are present in the injected CO_2, the proportion of immiscible and near-miscible states increases as the CO_2 purity decreases. This is because the mixing of impurity gases reduces the dissolution and diffusion effects of CO_2 in crude oil. However, the impact of methane on CO_2-crude oil miscibility is slightly less than that of nitrogen.

Tab. 5 The multi-type miscible state proportion and flow coefficient under different influencing factors

Influencing Factors	Value	Immis, %	Near-Mis, %	Mis, %	Full-Mis, %	Recovery, %
Injection PV Number	0.9	39.5	17.7	34.5	8.3	58.607
	1.0	36.4	16.3	37.2	10.1	59.123
	1.1	34.6	15.1	38.1	12.2	59.815
	1.2	31.6	14.7	40.1	13.6	60.376
N_2 Content in Injected Gas, %	0	36.4	16.3	37.2	10.1	59.815
	5	49.5	21.6	19.7	9.2	52.889
	10	54.0	24.7	14.9	6.4	46.086
	20	59.4	26.8	10.2	3.6	41.141
CH_4 Content in Injected Gas, %	0	36.4	16.3	37.2	10.1	59.815
	5	35.6	24.9	30.5	9.0	57.479
	10	40.0	32.6	19.6	7.8	52.428
	20	48.5	34.4	10.5	6.6	45.988

4. CONCLUSIONS

In the H block of the JY Oilfield, the crude oil is medium-light. PVT experiments measured a saturation pressure of 4.762 MPa. After dissolving CO_2, the viscosity of the crude oil decreased by approximately 30%, while the gas-oil ratio, saturation pressure, and volume expansion coefficient increased. Capillary tube experiments measured the minimum miscibility pressure (MMP) of CO_2-oil at reservoir temperature to be 17.26 MPa, corresponding to oil recovery of 91.4%.

The one-dimensional numerical capillary tube experiment simulation yielded an MMP of 17.28 MPa, with a deviation of 0.11% from the experimental result. Based on oil recovery and interfacial tension variation, the CO_2-oil miscibility states were classified into four types: immiscible, near-miscible, miscible, and full miscible. As the water saturation increases, the threshold for the minimum miscibility pressure rises, the pressure range for different miscibility states narrows, and oil recovery decreases.

The pore size effect and residual water shielding effect are the main factors affecting the miscibility state of CO_2 injection in low-permeability reservoirs. The crude oil flow coefficient was used to characterize the variation patterns and main controlling factors of CO_2-oil miscibility states. When water saturation increases, the effectiveness of CO_2 in improving crude oil flow capacity decreases. At high water saturation, the interfacial tension between CO_2 and oil becomes unstable under full miscible conditions, and the effect of the miscibility state on improving crude oil flow capacity is similar to that of the full miscible state.

Factors such as the number of injected pore volumes (PV) and the purity of injected CO_2 influence the CO_2-oil miscibility state. When the number of injected PVs increases, the reservoir pressure remains high, primarily driving with miscible and full miscible states. When impurity gases such as nitrogen or methane are present in the injected CO_2, the dissolution and diffusion of CO_2 in crude oil are hindered. The higher the impurity gas content, the higher the proportion of immiscible and near-miscible states. However, methane has a slightly lower impact on the miscibility state and oil displacement efficiency compared to nitrogen.

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