Carbon Dioxide Flooding Technology for Ultra-Low Permeability Reservoirs to Greatly Enhance oil Recovery

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Abstract. Low-permeability reservoir pressure is difficult to maintain, CO$_2$ miscible flooding is difficult to achieve for low-permeability reservoirs, and near-miscible flooding is a promising technology for enhancing oil recovery for low-permeability reservoirs. Aiming at the complex geological and development characteristics of China's continental low-permeability reservoirs, the system elaborated Sinopec’s CO$_2$ flooding theory, reservoir engineering optimization design, injection and production engineering and anti-corrosion technology, production CO$_2$ recovery and utilization, and other technical developments and field tests. Happening. Based on the research of CO$_2$ flooding mechanism, this paper takes a well-known oil field H 28 reservoir as the target, and conducts an indoor evaluation of CO$_2$ flooding methods through core physical simulation experiments. The pilot test of CO$_2$ flooding field shows that CO$_2$ flooding can significantly increase the productivity of ultra-low permeability oil wells, improve the development effect of oil wells, and meet the needs of ultra-low permeability reservoir development, and has broad application prospects.

Key words. Glutamate medium and low permeability reservoirs, carbon dioxide flooding, minimum miscibility pressure, oil displacement efficiency.

1. Introduction
With the development of the national economy, China's oil consumption continues to grow, and the contradiction between oil supply and demand has become increasingly prominent. In 2018, the total domestic oil consumption was $6.48 \times 10^8$ t, the total import amount was $4.62 \times 10^8$ t, and the foreign dependence rate was as high as 70%. The oil supply security situation is severe. Therefore, maintaining the stability of oil production is crucial to ensuring China's energy security. CO$_2$ has good solubility and strong extraction ability in crude oil, which can greatly reduce the viscosity of crude oil, swell and increase its capacity, and reduce interfacial tension by contacting with crude oil for multiple times, thereby greatly improving oil recovery [1]. Field practice shows that compared with water flooding, the CO$_2$ absorption index can be increased by 5 times and the starting pressure can be reduced by 50%, which greatly improves the injection capacity and effectively solves the problem of "non-injection and recovery" in the development of low-permeability reservoirs. Problems such as no production, low oil recovery rate, and low recovery rate. At the same time, the injected CO$_2$ can be stored underground on a large scale, realizing high-efficiency CO$_2$ emission reduction. Therefore, CO$_2$ flooding is one of the
effective technologies for low-permeability reservoirs to enhance oil recovery, reduce CO₂ emissions, and utilize resources. Therefore, for a well-known ultra-low-permeability oil reservoir, an indoor experimental study of CO₂ injection to enhance oil recovery was carried out, and on this basis, field tests were carried out to obtain CO₂ flooding for this type of ultra-low-permeability reservoir. Early understanding.

2. CO₂ flooding mechanism

At present, there are mainly three recognized CO₂ flooding mechanisms: 1) Miscible flooding, which realizes the miscibility of CO₂ and crude oil through multiple contacts. There are two mechanisms of evaporative miscible and condensate miscible. Miscible flooding efficiency is high, but formation pressure is required [2]. Above the minimum miscible pressure. 2) Immiscible flooding. Due to low formation pressure or poor crude oil properties, CO₂ reduces crude oil viscosity, swells formation oil and reduces interfacial tension, but the displacement efficiency is low. 3) Near-miscible flooding. ZICK proposed the concept of near-miscible flooding in 1986. In 1995, SHYEH-YUNG et al. extended the concept of near-miscible flooding and proposed that near-miscible gas flooding means that the injected gas is not completely miscible with oil, but close to miscible state.

Traditional CO₂ miscible flooding theory believes that reservoirs with formation pressure lower than the minimum miscible pressure belong to immiscible flooding. However, for low-permeability reservoirs, the distribution of formation pressure field will change significantly during the gas injection development process, and the influence of reservoir pressure spatial changes on the CO₂ miscible state cannot be ignored. For example, in the development of CO₂ flooding in low-permeability reservoirs in some Oilfield, the pressure near the bottom of the injection well is generally greater than 40 MPa, which is far greater than the minimum miscible pressure, while the pressure near the bottom of the production well is about 15 MPa, which is much less than the minimum miscible pressure [3]. This means that there is miscible flooding near the injection wells and immiscible flooding near the production wells. Therefore, if a single miscible or immiscible phase is used to qualitatively describe the CO₂ displacement process of a low-permeability reservoir, it cannot fully reflect the distribution of the miscible state, which has great limitations. Based on this, the theory of imperfect miscible flooding is proposed, which takes into account the influence of the pressure profile between injection and production wells on the displacement process, which more reflects the actual process of CO₂ flooding in low-permeability reservoirs.

CO₂ imperfect miscible flooding is to accurately predict the pressure field, saturation field and component concentration field of the reservoir through the coupling and restriction of the dynamic process and the thermodynamic process, which is determined according to the formation pressure distribution, the component concentration distribution and the minimum miscible pressure Reservoir miscible state, which reflects the miscible state of CO₂ and crude oil in the reservoir, interfacial tension, oil gas density and viscosity and other time-varying and space-variable characteristics, and accurately describes the miscible and non-miscible status from the injection well to the production well profile. There are three states of complete miscibility and immiscibility, instead of just relying on average formation pressure and minimum miscibility pressure to determine whether the reservoir is a miscible or immiscible flooding process [4]. The process of CO₂ imperfect miscible flooding involves the thermodynamic equilibrium of multiple components and the conservation of component materials. The mass transfer law is far more complicated than that of water flooding. There are two fronts: phase front and component front. Accurately describe the incomplete miscibility state of CO₂ flooding in the reservoir. Generally, physical simulation experiments, fine geological modelling, and component numerical simulation are combined to couple the dynamic process and thermodynamic process to quantitatively characterize the pressure field, saturation field, and concentration field. The dynamic changes of the interfacial tension field and physical properties, and then understand the regularity of the miscible state in the CO₂ flooding process, and provide technical support for improving the development effect of CO₂ flooding. Figure 1 shows the CO₂ flooding mechanism.
3. Deep-seated low-permeability CO$_2$ flooding technology for enhanced oil recovery

3.1. The minimum miscible pressure and its influencing factors

3.1.1 Minimum miscible pressure. The minimum miscible pressure (MMP) is one of the key factors that affect CO$_2$ flooding to increase the recovery rate. At present, the calculation and measurement of the minimum miscible pressure at home and abroad are based on the original oil of the reservoir. The fluid properties of the target reservoir are close to volatile oil. After depletion development, dissolved gas is produced, the composition of crude oil changes greatly, and the content of intermediate hydrocarbons rises [5]. To this end, the use of long thin tube laboratory experiments to determine the minimum miscible pressure, to study the crude oil miscible pressure and the change of the minimum miscible pressure under different depletion pressures.

3.1.2 Factors affecting the minimum miscible pressure. The current formation fluid is used to prepare the experimental oil according to the original state of the formation, and the pressure is depleted to different stages under the original formation pressure. The saturated pressure of the crude oil is 37.94, 28.43, 20.16, 15.01, 10.05, and 5.13 MPa, and the minimum is measured. Miscible pressure. It can be seen from Table 1 that the lower the saturation pressure, the lower the corresponding minimum miscible pressure. Therefore, in the actual formation, due to the existence of the pressure drop funnel, the minimum miscible pressure is dynamic, which is a new understanding that has formed; at the same time, it also shows that in the actual formation, the displacement mechanism is no single, but rather miscible and non-uniform. The combination of mixed phases.

| Saturation pressure/MPa | 37.94 | 28.43 | 20.16 | 15.01 | 10.05 | 5.13 |
|-------------------------|-------|-------|-------|-------|-------|------|
| Minimum miscible pressure/MPa | 37.89 | 29.17 | 22.56 | 18.19 | 15.04 | 12.48 |

At the same time, the minimum miscible pressure experiment of crude oil under different hydrocarbon components was carried out. The experiment added a single component to the original fluid, and then measured the change of the minimum miscible pressure before and after the addition, and then calculated the increase of a certain amount of the component to the miscible pressure impact. The measurement results are shown in Table 2. Research shows that the intermediate hydrocarbon...
components of crude oil reduce MMP, while the light gas and heavy hydrocarbon components will increase MMP. The resulting understanding can be used as a reference for purposeful gas injection production.

Table 2. The minimum miscible pressure changes corresponding to the changes of different hydrocarbon components

| Hydrocarbon component (10% increase) | C1  | C2  | C3  | C4  | C5  | C6  | C7-C9 | C10-C15 | C16 | N2   |
|-------------------------------------|-----|-----|-----|-----|-----|-----|-------|---------|-----|------|
| MMP change range/%                  | 14.34 | -4.90 | -7.90 | -9.04 | -9.24 | -15.99 | -6.24 | -2.64 | 10.74 | 25.94 |

3.2. Optimization of CO$_2$ flooding parameters in deep low-permeability reservoirs

3.2.1 Optimization of gas injection volume. In CO$_2$ flooding, the recovery factor increases with the increase of CO$_2$ consumption, but after the CO$_2$ consumption reaches a certain level, the recovery factor increases less and less. Therefore, the amount of CO$_2$ should be reasonably selected through laboratory experiments according to reservoir characteristics and drive types [6]. For this reason, long-core laboratory experiments are used to carry out gas injection optimization research. The research shows that as the number of CO$_2$ injected into HPV increases, the recovery rate increases, and the oil exchange rate shows a downward trend. Continue to inject CO$_2$, and change the oil with the increase of CO$_2$ consumption. The rate of decline gradually slowed down. According to the experimental results, the optimal gas injection rate of the research block is 0.40HPV, the average oil change rate is 0.57t/t, and the incremental oil change rate is 0.25t/t, which is close to the economic limit.

3.2.2 Optimization of injection method. This thesis uses two methods of long core displacement experiment and numerical simulation to explore the development effects of three different injection methods of direct CO$_2$ injection, formation pressure recovery to 34.00MPa and CO$_2$ injection, formation pressure recovery to 40.00MPa and CO$_2$ injection. The experimental results show that when the same multiple of CO$_2$ is injected, the higher the formation pressure recovery, the higher the oil displacement efficiency (Table 3). Therefore, for low-permeability reservoirs that have been developed with natural energy, the formation energy should be restored before gas injection to achieve higher recovery.

Table 3. Comparison of experimental results of CO$_2$ injection to restore formation pressure development methods

| Mining method                          | Depletion mining recovery degree/% | Improve recovery rate/% | Final recovery rate/% |
|----------------------------------------|----------------------------------|------------------------|----------------------|
| Direct CO$_2$ injection (1.46HPV)       | 19.40                            | 66.70                  | 86.10                |
| Recovery 34.0MPa CO$_2$ injection      | 19.40                            | 71.70                  | 91.10                |
| (1.45HPV)                              |                                  |                        |                      |
| Recovery 40.0MPa CO$_2$ injection      | 19.30                            | 79.00                  | 98.30                |
| (1.52HPV)                              |                                  |                        |                      |

3.3. CO$_2$ flooding efficiency with different back pressures
The slim tube experiment shows that the miscible pressure of CO$_2$ and the crude oil of H 28 reservoir in the Oilfield is 20.2MPa, the back pressure of CO$_2$ miscible flooding is set to 21MPa, and the back pressure of CO$_2$ immiscible flooding is 8MPa. According to the experimental data, the oil displacement efficiency curves of CO$_2$ miscible flooding and immiscible flooding are made, as shown in Figure 1.
Figure 2. CO$_2$ flooding efficiency curve under different back pressures

It can be seen from the experimental data that in the CO$_2$ miscible flooding, after CO$_2$ injection is started, the inlet pressure continues to increase, and the oil production also continues to increase. When the PV number of CO$_2$ injection is 2.3, the injection pressure reaches the maximum, and then the gas breaks through. The injection pressure decreases, the gas-oil ratio increases slowly, and the oil production still increases rapidly. When the PV number of CO$_2$ injected is 3.5, the gas-oil ratio increases rapidly, the oil production rate decreases rapidly, the displacement pressure stabilizes at 2.2 MPa, and the crude oil recovery rate finally reaches 83.98%. It can be seen that, compared with CO$_2$ immiscible flooding, miscible flooding has higher oil displacement efficiency and lower displacement pressure [7]. This is because the interfacial tension of crude oil decreases after miscibility, which reduces the displacement pressure gradient; at the same time, compared to CO$_2$ immiscible flooding. For immiscible flooding, the injection volume of miscible flooding during CO$_2$ breakthrough is higher than that of immiscible flooding. This is because after CO$_2$ and crude oil reach the miscible phase, the viscosity of the crude oil decreases more than immiscible flooding, which can improve the mobility ratio and slow down the CO$_2$ fingering, and delay the gas channelling of CO$_2$ to a certain extent.

3.4. CO$_2$ flooding efficiency without displacement

The paper set the core outlet back pressure to 21 MPa, the pressure of each vessel was replaced to 20 MPa in advance, and water flooding plus CO$_2$ miscible flooding and CO$_2$/water alternate flooding were performed respectively, and water with a PV number of 0.1 and CO$_2$ of 0.1 were alternately injected at a constant rate. During the experiment, the displacement pressure difference, oil, gas, and water output after the injection of each slug were recorded respectively, as shown in Figure 2.
4. Technical characteristics of CO₂ flooding in deep low-permeability reservoirs

4.1. CO₂ reduces the volumetric expansion viscosity of crude oil
As the amount of CO₂ injected increases, the CO₂ dissolved in crude oil also increases, and the saturation pressure also rises. The more CO₂ injected, the higher the saturation pressure. This shows that the formation crude oil has a strong ability to dissolve CO₂, and the amount of gas injection will affect the miscible conditions of the injected gas and crude oil. As the gas injection volume increases, the miscible pressure tends to increase.

4.2. Crude oil volume expansion
Indoor PVT experiment results show that when the gas-oil ratio of dissolved CO₂ in crude oil reaches 39.9m³/m³, the volume coefficient of crude oil increases from 1.169 to 1.318, and the density of crude oil decreases from 0.799g/cm³ to 0.714g/cm³. The volume expands after dissolving CO₂, which promotes the increase of the pore volume filled with oil, which provides favourable conditions for the oil to flow in the pore medium. At the same time, the swollen oil droplets squeeze the water out of the pore space, making the water-wet system form a kind of drainage instead of in the process of water absorption, phase permeability conversion occurs, which can form a favourable environment suitable for oil flow under any saturation conditions.

4.3. Improve permeability
Through indoor core flow experiments, the permeability of the same core in the formation water and saturated CO₂ of the same core in the H 28 reservoir of Oilfield was measured. At the same time, the content of calcium and magnesium ions in the produced fluid at different times was measured. It can be found that the injection flow rate is constant. In this case, the permeability tested with formation water is 0.0075×10⁻³μm², and the permeability tested with formation water saturated with CO₂ is 0.054×10⁻³μm²; meanwhile, the mass concentration of calcium in the formation water drive fluid after saturated with CO₂ Compared with formation water flooding alone, the Ca²⁺ mass concentration increased by
1075 mg/L, with an increase of 20.4%, and Mg\(^{2+}\) increased by 243.4 mg/L compared with formation water, with an increase of 30.0%.

5. Conclusion
Compared with immiscible flooding, the recovery rate of near-miscible flooding is greatly improved, which slows down the breakthrough of gas; the displacement efficiency of near-miscible flooding is slightly lower than that of miscible flooding, but the affected area is larger than that of miscible flooding, so the final recovery efficiency of the two is not much different. Pressure, temperature, and the content of impurities in CO\(_2\) gas will all have a certain impact on the near-miscible flooding, which mainly changes the minimum miscible pressure of the CO\(_2\)-crude oil system. Therefore, it is recommended to maintain the formation pressure in the mineral test, select the lower temperature reservoir, and reduce Impurity content in injected CO\(_2\).

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