A Comparative Study on Enhancing Oil Recovery of CO₂ Miscible Displacement with Several Displacement Ways in an Extra-low Permeability Reservoir

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Abstract: Efficiency of oil recovery with water flooding process is poor in low permeability oil reservoirs. By contrast, gas flooding is an efficient technology to improve oil recovery of such reservoirs. Considering good results of previous miscible displacements, experiments of physical model are performed by using the long core flow test, and variations of recovery factors and pressure are obtained under the different flooding processes in miscible pressure condition. In this paper, it includes pure gas flooding, pure water flooding, gas flooding after water flooding, water flooding after gas flooding and WAG. The research will provide the principle for selection of reasonable development manner of low permeability reservoirs and basic data for further numerical simulation.

Key words: gas, MMP, near miscible displacement, EOR, low permeability

1 Introduction

Gas miscible displacement shows much more advantages than other enhanced oil recovery ways. During process of Gas miscible displacement, Interfacial tension is close to zero and displacement efficiency is towards to 100 percent theoretically. Final reservoir recovery is normally beyond 60%, and it will reach 90% when this technology is combined with mobility control technology. So, Gas miscible displacement has been paid much attention.

Yushulun reservoir in DaQing is of low permeability, low production, low abundance with burial depth ranging from 1500 to 2200 m, average air permeability is $3.5 \times 10^{-3} \mu \text{m}^2$, average effective porosity is 13.1%, reservoir temperature is 90℃, density of degassing crude oil is 0.85 g/cm³, underground oil viscosity is 3.3 mPa·s, volume factor is 1.104, gas oil ratio is 22 m³/t.

For the sake of strong heterogeneity, in order to inhibit CO₂ channeling and upgrade sweep efficiency, WAG is often performed usually in oilfields. Combined with previous experiences of pure gas flooding and pure water flooding, according to real reservoir situations, five different group experiments, which exam different type of displacement’s influence on oil recovery in miscible pressure and provide references for reservoir exploitation, are set up in this paper.

2 Minimummiscibility pressure

2.1 Experimental raw materials and experimental apparatuses

<table>
<thead>
<tr>
<th>TABLE 1</th>
<th>Gas and crude oil components</th>
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<tbody>
<tr>
<td><strong>Gas composition</strong></td>
<td></td>
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<tr>
<td>component</td>
<td>methane</td>
</tr>
<tr>
<td>v%</td>
<td>92.1</td>
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<tr>
<td><strong>Crude oil composition</strong></td>
<td></td>
</tr>
<tr>
<td>Number of carbon</td>
<td>C₆-₁₃</td>
</tr>
<tr>
<td>component</td>
<td>17.15</td>
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</tbody>
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2.1.2 Experimental parameters of slim tube

The main experimental apparatuses are shown below:

i. injection pump: Ruska automatic pump which pressure range is 0~70 Mpa;
ii. electronic differential pressure gauge: precision is 0.001 Mpa;
iii. incubator: the maximum temperature is 200ºC;
iv. gasometer: precision is 1ml;
v. otational viscometer;
vi. gas chromatography.

<table>
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<th>TABLE 2  Slim tube coefficient</th>
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<tr>
<td>long length (m)</td>
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<td>7.67</td>
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2.2 Experimental result and discussion

It is quoted that the miscible displacement can be explained the lowest pressure at which CO₂ containing injection fluid can develop miscibility with the reservoir temperature is defined as the minimum miscibility pressure (MMP) and commonly abbreviated as MMP. Experimental method is the best choice for determining MMP. In application of engineering, the lowest pressure is the one at which ultimate oil recovery reaches 90% at reservoir temperature. Furthermore, we think that crude oil and CO₂ become miscible when reservoir pressure is beyond MMP.

As the figure 1-1 upper line showing, the lowest pressure also called MMP would reach when the crude oil recovery reach 90% with the injection volume of 1.2HCTV. Therefore, MMP of gas and crude oil, taken from YuShuLin reservoir in DaQing, is 20 Ma.

![FIGURE 1 Relation diagram of experimental pressure and oil recovery](image)

3 Long core flooding experiment

3.1 Experimental apparatus

The only difference between long core experiment and slim tube is that long core holder is in the replacement of slim tube. Measure method of long core experiment is as same with that of slim tube, and, sensitivity is same too.

3.2 Experimental results and discussions

3.2.1 Relation of injection volume and GOR in miscible pressure

In the condition of 20MPa, Gas flooding tested firstly, then it would be conducted by 1.3HCPV gas flooding followed by water flooding, and then it would be tested in inverse order. In the situation of 0.15HCPV WAG, it would influence the recovery by the following five different displacement methods, which includes pure gas flooding, gas-water flooding, water-gas flooding, WAG and pure water flooding.
flooding.

The influence of oil recovery on pure gas flooding, water flooding after 1.3 HCPV gas flooding, gas flooding after 1.3 HCPV water flooding and 0.15 HCPV WAG, pure water flooding (abbr. as gas flooding, gas-water flooding, water-gas flooding, WAG and water flooding) are studied in this paper.

3.2.1 Relation of injection volume and GOR in miscible pressure

Figure 2 shows that GOR would change with injection volume in the method of gas-water flooding, water-gas flooding, and WAG. Gas production with injection volume in 5MPa, 15MPa, 20MPa and 30MPa displacement pressure are displayed in figure 3.

CO₂ breaks through when injection volume is 1.0 HCPV in 5 and 15 Mpa. While CO₂ breaks through when injection volume is 1.1 HCPV in 20 and 30 Mpa. That is to say, it is easy for pure CO₂ flooding and water-CO₂ flooding to break through in low displacement pressure.

After CO₂ breaks through, gas production would increase quickly as the pressure does. Therefore, it can be concluded that even for immiscible displacement, it is not suitable for too low displacement pressure.

During process of gas-water flooding and WAG, especially that of WAG, GOR changes a little. In reservoir exploitation, GOR increases quickly in high pressure in such situation. WAG could inhibit gas channeling, increase sweep area, reduce amount of CO₂ and upgrade utilization ratio of CO₂.

![FIGURE 2 Relation diagram of injection volume and GOR in 20 Mpa](image)

![FIGURE 3 Relation diagram of injection volume and gas production](image)

3.2.2 Relation of injection volume and injection/production pressure difference in miscible pressure

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Injection/production pressure differences with injection volume are displayed in figure 4. Entrance and outlet pressure differences of long core in this experiment stimulate injection/production pressure differences in reservoir exploitation.

Figure 4 shows that injection/production pressure difference of pure gas flooding is much higher than that of WAG; injection/production pressure difference of gas-water flooding is high before 1.3 HCPV, moreover, that of water-gas flooding is high after 1.3 HCPV.

Therefore, the results indicate that injection/production pressure difference and resistance of multiphase flow in porous media concentrate on gas flooding plug. Solubility of gas in crude oil increase, interfacial tension between gas and crude oil decrease, viscosity of crude oil decrease and volume is expand with the increase of injection pressure; at the same time, flow ability of crude oil in the strata increase with enough formation energy.

3.2.3 Relation of injection volume and water contend in miscible pressure

After pure gas flooding which makes water contend decrease rapidly, oil production is poor, which shows that water flooding is much better than gas flooding at the beginning of reservoir exploitation.

After 1HCPV waterflooding injection, gas flooding is performed in this Laboratory, which stimulates reservoir exploitation in high water cut after water flooding. Considering of previous good results of miscible pressure, Changing of Water Content, injection/production pressure difference and oil recovery are studied in the miscible pressure. Therefore, it is good for gas flooding to maintain strata pressure and maintain strata energy, which is better than waterflooding. Figure 5 shows that ultimate oil recovery is 65.8% with gas flooding after water flooding, which is almost equal to that of pure gas flooding. So, it is feasible to perform gas flooding after water flooding in high water cut in the theory.
3.2.4 Relation of injection volume and oil recovery in miscible pressure

**FIGURE 6  Relation diagram of oil recovery with different type of injection in 20 MPa**

**FIGURE 7  Relation diagram of final oil recovery with different type of injection in 20 Mpa**

Figure 6 and figure 7 show that oil recovery increase gradually, as far as water-gas flooding concerned, which indicate that it is feasible for reservoir in high water cut to perform CO\textsubscript{2} flooding.

Oil recovery of pure gas flooding, gas-water flooding, water-gas flooding, WAG and pure water flooding are 72.1%, 66.7%, 58.1%, 62.3% and 42.3% respectively, that is to say, Oil recovery of pure gas flooding is higher than that of WAG.

After WAG, Oil, Gas and Water Three Phase Flow increase percolating resistance of water displacement and change suction profile; and gas gravity segregation sweep remaining oil on the top of strata. WAG inhabit increasement of Water Content and GOR, moreover, Three Phase Flow increase lead to decrease of oil phase permeability. Therefore, not considering strong heterogeneity of fracture reservoir, pure large plug gas flooding is better than WAG; Considering fractured reservoir with strong heterogeneity, WAG can increase sweep volume. Therefore, WAG is performed in real reservoir exploitation.

**Conclusions**
1. There are some of blocks which has not been exploited, some of them in high water cut stages of their development by water flooding in this fracture reservoir. For the block which has not been exploited, pure gas injection should be performed as well as the block in high water cut stages of their development; for fracture reservoir with strong heterogeneity, in order to inhabit gas channeling, WAG should be used.

2. Ultimate oil recovery of pure gas flooding can reach 72.1% in miscible pressure, which displays a good result of gas miscible displacement. After CO₂ breaks through, gas production would increase quickly as the pressure does. Therefore it can be concluded that even for unmiscible displacement, it is not suitable for too low displacement pressure.

3. Ultimate oil recovery, which is almost equal to that of pure gas flooding, is 65.8% when gas flood after water flood. So, it is feasible to perform gas flooding after water flooding in high water cut in the theory.

4. When WAG is performed in miscible pressure ultimate oil recovery is 42.3%, which is lower than ultimate oil recovery, 66.7%, got from pure gas injection. So, a continuous large gas plug will acquire a good result when gas channeling is not obvious. Under the Consideration of strong heterogeneity, especially fracture reservoirs, WAG is often applied in real reservoir exploitation. During this process, gas rapid breakthrough is inhibited and oil recovery is upgraded.

References