Enhanced oil recovery by CO$_2$–CH$_4$ flooding in low permeability and rhythmic hydrocarbon reservoir

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Abstract
To promote CO$_2$ utilization and protect the environment, CO$_2$ is often employed to enhance oil recovery. Meanwhile, injection of CO$_2$–CH$_4$ mixtures can offer better mobility ratios and delay water breakthrough resulting in the favorable oil sweep efficiency. The gas-alternating-water (WAG) flooding in rhythmic hydrocarbon reservoirs has been studied by simulation software. The difference between water and CO$_2$–CH$_4$ flooding lies in the different density and viscosity among CO$_2$, CH$_4$, oil and water. Water tends to displace oil along the lower reservoir; inverted rhythmic reservoir may slow down the trend. CO$_2$ and CH$_4$ tend to displace oil along the middle-upper and upper reservoir, respectively; positive rhythmic reservoir may slow down the trend. Therefore, a homogeneous reservoir should be given priority in WAG flooding, followed by positive rhythmic reservoir.

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Introduction
Greenhouse gases emissions are commonly identified as a major contributor to global warming. A great quantity of CO$_2$ from industrial generation facilities is being emitted, which is facing serious challenges in deploying CO$_2$ capture and storage (CCS) at large-scale due to relatively high costs, and it is experiencing significant shortages in CO$_2$ supply to expand oil production through enhanced oil recovery (EOR) [1]. According to the statistics, more than 80 percent of the CO$_2$-EOR used came from natural CO$_2$ underground reservoirs, the rest of the CO$_2$ used came from anthropogenic sources that emit high purity CO$_2$ streams, especially natural gas processing and coal gasification plants [2]. Today, CO$_2$-EOR shows great potential in reducing CO$_2$ emissions by means of sequestrating CO$_2$ underground and bridges the gap between CO$_2$ supply and demand while promotes CO$_2$ utilization and protects the environment against pollution [3].

CO$_2$-EOR has been widely accepted as an effective technique in oilfields, which has been in continuous operation and expansion since it was first commercially tested in the 1950s [4–6]. Due to the limited economy situation, until the late 1970s, the implementation of the CO$_2$ injection project finally succeeded [7–9]. It is often used as an EOR process where it is injected following by water flooding in order to enhance oil recovery. Further, gas–gas mixing is now well-acknowledged to be a function of viscosity, density and other physical properties of the gases. This mixing of CO$_2$ and CH$_4$ is governed in different heights of the main convective flux due to different density among them. Moreover, when both phases are in contact, laterally, gas mixing results from molecular diffusion and Taylor dispersion [10]. Recent study focused on CO$_2$ storage in combination with enhanced oil recovery show limited mixing for CH$_4$ displaced by CO$_2$ in hydrocarbon reservoirs [11].
Generally speaking, water flooding is often used to supplement the reservoir energy, which has higher development efficiency in medium- and high-permeability reservoirs. However, this method often shows the low oil recovery efficiency resulting from the great difference of density and viscosity between the water and oil, which easily lead to water fingering, override and channeling for low permeability reservoirs. In addition, due to exiting capillary pressure and threshold pressure gradient, little water is injected, whereas it is difficult to supply the reservoir energy. CO$_2$/CH$_4$ flooding is easily injected and very suitable for hydrocarbon reservoirs with low permeability, and a feasible alternative for water flooding [12,13].

Many studies show that CO$_2$/CH$_4$ miscible/immiscible flooding can reduce oil viscosity when they dissolve into the oil. CO$_2$–CH$_4$ flooding is more suitable for low permeability reservoirs [14–16]. Recently, the oil in place with low permeability hydrocarbon reservoirs approximately has taken up 60 percent of the proved reserve which has not been developed in the world. In the case of a rapid growth in energy demand, it is of increasing importance how to efficiently develop low permeability reservoirs and become a major potential for steady sustainable development of petroleum industry in the future [17,18]. The mechanism of CO$_2$–CH$_4$-EOR has already been quite clear and the technology application has obtained certain success in the oilfield, but the project for CO$_2$–CH$_4$ flooding endures great risk [19,20]. The injection modes in CO$_2$/CH$_4$ flooding have critical influences on EOR and CCS potential [21]. There are three major types in gas flooding: continuous gas flooding, gas alternative water (WAG) flooding and cyclic gas stimulation (or huff ‘n puff). WAG flooding is widely used and can enhance oil displacement efficiency in vertical direction and gain a higher oil recovery. WAG flooding can improve sweep efficiency of gas injection mainly by utilizing the water to control the mobility of the displacement and to stabilize the flooding front [22].

However, to the best of our knowledge, aimed at WAG flooding, previous researches mainly focused on the simulation evaluation in homogeneous hydrocarbon reservoir. Few literature are available on the WAG flooding in a different low-permeability rhythm hydrocarbon reservoirs during production. This paper reports concerning a WAG flooding simulation research in typical low permeability LLP block in Jilin oilfield, China, that were undertaken with the objective of identifying the impact of WAG flooding on the oil recovery in different low permeability and rhythm hydrocarbon reservoirs. The different low permeability rhythmic hydrocarbon reservoirs have the different development strategies. The research has a very important significance on priority to select different development program in the low permeability rhythmic hydrocarbon reservoir.

### Numerical simulation

#### Input parameters

According to the typical low permeability data of LLP block in Jilin oilfield, the component model of the Eclipse software used for simulation of WAG flooding and the input parameters were listed as: porosity 12%, thickness 5.0 m, depth 2500 m, the original formation pressure 25 MPa and the initial oil saturation 70%. A five-spot pattern well group was used and the well spacing was 300 m.

The crude oil was characterized by tuning the properties of pseudo components in a phase equilibrium package. An accurate experimental test provided pseudo-components description of crude oil were listed as: mole fractions (%) of C$_1$ to C$_{14}$ to C$_{15}$ to C$_{16}$ were 16.69, 12.18, 27.18, 27.52 and 16.43, respectively. Although the results of the ideal model may be of notable difference compared with that of the actual situations, but the conclusions drawn would also have important significance in actual oilfield application.

The optimal CO$_2$/CH$_4$ volume ratio was selected as 4:1 in the early screening based on the laboratory experiments and computational studies, which had the maximum oil displacement efficiency in the same porous medium.

#### Simulation schemes in different rhythm reservoirs

The simulation schemes were supposed to have five layers. The first type was a homogeneous hydrocarbon reservoir, and its permeability of each layer was equal with X- and Y-permeability (10 $\times$ 10$^{-3}$um$^2$) and Z-permeability (1 $\times$ 10$^{-3}$um$^2$). The second type was a positive rhythm hydrocarbon reservoir, its permeability ratios of five layers were 1:2:4:8:16 from top to bottom with X- and Y-permeability (10 $\times$ 10$^{-3}$um$^2$) and Z-permeability (1 $\times$ 10$^{-3}$um$^2$) for the third layer. The third type was a positive rhythm reservoir, its permeability ratios of five layers were 16:8:4:2:1 from top to bottom and the same permeability as the second type for the third layer.

#### Simulation conditions

Based on the production status of LLP block, when WAG displaced the oil, gas slug was firstly injected with an injection rate of 10 000 m$^3$/d and injection time of 180 days. Subsequently, water slug was injected with injection time of 185 d. According to the previous optimization, the numbers of the injected slugs were 7 and the total volume of gas injection slugs was 0.3635 PV (pore volume). WAG flooding was then followed by continuous water flooding until the maximum limit water cut was 98% or the limit gas-oil ratio (GOR) was 5000 m$^3$/m$^3$ in all the oil wells.

#### Determination of the minimum miscibility pressure

The minimum miscibility pressure (MMP) is the most important parameter, which determines whether WAG flooding was miscible or immiscible. The widely applied experimental method named slim tube test was firstly proposed to determine the MMP. The reservoir fluid type in the region of interest belonged to black oil, and the reservoir was characterized experimentally by temperature (98 °C), original formation pressure (25 MPa), saturation pressure (9.43 MPa), viscosity of degassed crude oil (2.1 mPa·s at 98 °C), its density (0.812 g/cm$^3$ at 20 °C), and GOR (31.4 m$^3$/m$^3$). In the slim tube test, six experimental pressure points were selected around the reservoir pressure and then the oil recovery of the
corresponding pressure was recorded. According to the intersection of two straight lines, the MMP was determined as 21.80 MPa. Therefore, Mixtures of CO₂ and CH₄ can achieve the miscible flooding in the original formation pressure (25 MPa).

### Table 1 – Comparison of the production index in different rhythm reservoirs by WAG flooding.

<table>
<thead>
<tr>
<th>Reservoir type</th>
<th>Production time (a)</th>
<th>Oil recovery (%)</th>
<th>Cumulative water injection (10⁴ m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homogeneous</td>
<td>11.955</td>
<td>77.05</td>
<td>16.19</td>
</tr>
<tr>
<td>Positive rhythm</td>
<td>8.539</td>
<td>66.94</td>
<td>15.78</td>
</tr>
<tr>
<td>Inverted rhythm</td>
<td>6.436</td>
<td>59.66</td>
<td>9.58</td>
</tr>
</tbody>
</table>

**Results and discussion**

**Production index comparison**

Table 1 listed the simulation results by WAG flooding. From Table 1, CO₂ and CH₄ are easily injected to supply the reservoir energy and the different rhythm hydrocarbon reservoirs had the different oil recoveries. The oil recovery in homogeneous hydrocarbon reservoir was the highest with the maximal cumulative water injection and the longest production time, which indicated that it had the best oil displacement efficiency. The oil recovery in inverted rhythm reservoir was the lowest with the minimal cumulative water injection and the shortest production time, which indicated that it had the
worst oil displacement efficiency. In addition, positive rhythm hydrocarbon reservoir was located in the middle position.

Spatial distribution of oil saturation

Figs. 1–3 described the spatial residual oil saturation distribution in the different rhythm reservoirs by Eclipse software simulation including that (a) and (b) respectively showed the top and bottom bed for each figures.

Fig. 1 described the spatial oil saturation distribution in the top and bottom layers in the homogeneous reservoir. At the end of WAG flooding, the oil saturation of the top bed was lower than that of the bottom bed, which was opposite to that of conventional water flooding. The reason hence was that the density of CO₂ is lighter than that of oil, CH₄ is lighter than CO₂, CO₂ tends to displace the middle-upper oil and CH₄ tends to displace the upper oil, which both easily forms gas channeling along the middle-upper and upper part in a heterogeneous reservoir. However, water tends to displace oil along the lower reservoir. As a result, for WAG flooding, oil can be uniformly displaced in both the upper and the lower part resulting in the higher displacement efficiency.

Fig. 2 described the spatial oil saturation distribution in the top and bottom layers in the positive rhythm reservoir. At the end of WAG flooding, the oil saturation of the top bed was larger than that of the bottom bed. Because the permeability in upper part was less than that in the lower part, as a result, the gas channeling along the upper part was limited to a certain extent in positive rhythm reservoir, and the displacement efficiency was improved in the lower part.

Fig. 3 described the spatial oil saturation distribution in the top and bottom layers in the inverted rhythm reservoir. At the end of WAG flooding, the oil saturation of the top bed was lower than that of the bottom bed. Compared with positive rhythm reservoir, the gas channeling along the upper part was aggravated to a certain extent in inverted rhythm reservoir, and the displacement efficiency was lower in the lower part.

As a summary, according to the simulation results, when the implementation schemes are conducted by WAG flooding, the injection of CO₂–CH₄ mixtures can offer better mobility ratios which can mitigate the gravity override and channeling, and then delay breakthrough and obtain the favorable oil sweep efficiency.

Homogeneous hydrocarbon reservoir is given priority selection, followed by positive rhythm hydrocarbon reservoir, then inverted rhythm hydrocarbon reservoir. These conclusions have a very important significance in the priority of selecting different development program in low permeability and rhythmic hydrocarbon reservoir.

Conclusions

Based on the present work, the following conclusions may be drawn:

1) As indicated by the simulation results for CO₂–CH₄ flooding in different rhythm hydrocarbon reservoirs, CO₂ and CH₄ are easily injected to supply the reservoir energy. For homogeneous hydrocarbon reservoir, it was the highest oil recovery and had the best oil displacement efficiency. For inverted rhythm hydrocarbon reservoir, it had the worst oil displacement efficiency; the positive rhythm hydrocarbon reservoir was located in the middle position. CO₂–CH₄ is suitable for the different rhythm hydrocarbon reservoirs by WAG flooding.

2) According to the spatial oil saturation distribution in different rhythm hydrocarbon reservoirs, the oil can be uniformly displaced in both the upper and the lower part resulting in higher displacement efficiency in homogeneous hydrocarbon reservoir. The gas channeling along the upper part was limited to a certain extent in positive rhythm hydrocarbon reservoir, and the displacement efficiency was improved in the lower part. However, the gas channeling along the upper part was aggravated to a
certain extent in inverted rhythm reservoir, and the displacement efficiency was lower in the lower part. The injection of CO2—CH4 mixtures can offer better mobility ratios and mitigate the gravity override and channeling by WAG flooding.

3) Homogeneous hydrocarbon reservoirs are given priority during selection, followed by positive rhythm hydrocarbon reservoir, then inverted rhythm hydrocarbon reservoir. The results have a very important significance in the priority of selecting different development program in low permeability and rhythmic hydrocarbon reservoir.

Acknowledgments

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