Numerical Simulation of CO$_2$-N$_2$ Combination Flooding in Low Permeability-Ultra Low Permeability Homogeneous Reservoir

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Abstract: For low permeability, ultra-low permeability reservoir, the CO$_2$ preslug + N$_2$ flooding, using CMG numerical simulation software, the ideal homogeneous model which permeability is 3×10$^{-3}$μm$^2$ has been established. The recovery of CO$_2$ flooding under the 11 length-thickness ratios was calculated; the effects of 7 kinds of flooding slug combinations and 4 kinds of permeability on recovery with input-output ratio were analyzed; factors such as length-thickness ratio, permeability and injection slug combination affecting flooding effective were studied deeply. The result shows that: when the length-thickness ratio under the 100, as the increasing of the length-thickness ratio of the model, the oil recovery increased. When the length-thickness ratio reaches to 100, the oil recovery tends to be stabled, that is, when the single oil layer thickness less than 1% of the well spacing, it is more benefit to improve the oil recovery. As the permeability increases, the compound flooding recovery will decrease when the CO$_2$ injection (PV) is a constant and the CO$_2$ slug requires for the combination flooding to achieve the ultimate recovery increases, that is, the lower the permeability is, the more favorable it is for the CO$_2$-N$_2$ combination flooding. In actual oil reservoirs with a lengthen-thickness ratio of 30, the slug composition of CO$_2$-N$_2$ compound flooding should adopt the way of 0.3 PV CO$_2$ slug + subsequent N$_2$.

1. Introduction
Low permeability, ultra-low permeability reservoirs are usually characterized because of the low formation energy, low natural productivity and rapid formation pressure drop. For these reservoirs, water flooding development may not be a good way. Therefore, gas injection development has become a widely used technology to enhance oil recovery. CO$_2$ plays an important role in viscosity reduction, expansion, acidification and extraction of crude oil. The miscibility pressure of CO$_2$ and crude oil is low and CO$_2$ is easily injected into the low permeability reservoirs, so the oil recovery can be greatly improved. For CO$_2$ flooding, a lot of research has been done in China. The mechanism of CO$_2$ injection and the optimal application ideas were studied, and it was believed that CO$_2$ flooding could effectively realize the organic combination of burial, enhanced recovery, could provide theoretical and practical basis for the sustainable development of global petroleum resources at refs [1]. Through lab long-core physical simulation experiment, it is concluded that in the process of CO$_2$ driving, both oil displacement efficiency and gas breakthrough time increased when the permeability decreased at refs [2-3]. By means of lab physical simulation, the curve characteristics of different phases of immiscible, near-miscible and miscible were analyzed, and the determination method of near-miscible flooding region was established at refs [4]. By studying the method of improving the efficiency of CO$_2$ flooding in low permeability reservoir in middle and late stage, it is concluded that the effect of water-gas
alternation to improve the recovery is better at refs [5]. Numerical simulation was used to study the method to improve the effect of CO₂ injection and oil displacement. The results showed that injection of pre-light hydrocarbon slug could increase the degree of miscibility, delay the time of gas breakthrough, and improve the degree of oil reservoir production at refs [6]. Based on the study of the factors influencing the minimum miscible pressure of CO₂ flooding by numerical simulation, it is concluded that the minimum miscible pressure decreases with the decrease of methane and nitrogen concentration in crude oil at refs [7]. However, at present, domestic CO₂ gas sources are limited and CO₂ flooding field applications are few. Therefore, people consider using N₂ to partially replace CO₂ for low permeability-ultra low permeability reservoir development. By comparing the mechanism of CO₂ and N₂ oil displacement, it is concluded that the minimum miscible pressure of N₂ is higher than CO₂ and other factors, resulting in the fact that the recovery improvement effect of N₂ flooding is lower than that of CO₂ flooding at refs [8-9]. The displacement effects of continuous CO₂ injection, mixed CO₂ and N₂ injection and CO₂ preslug+N₂ injection were studied by numerical simulation. The results showed that a reasonable injection of CO₂ preslug+N₂ oil displacement method could give full play to the advantages of CO₂ and N₂ on the basis of reducing CO₂ consumption, and achieve the same oil displacement effect as continuous CO₂ injection at refs [10]. Therefore, aiming at the oil displacement mode of CO₂ preslug+N₂, CMG numerical simulation software was used to establish an ideal homogeneous model to study the influence of formation permeability, length-thickness ratio of the model, combination of injected slug and other factors on the oil displacement effect during slug injection, so as to achieve the purpose of effectively increasing recovery.

2. Ideal homogeneous model

In order to further study the reasonable slug size of CO₂ in CO₂-N₂ combination flooding and prevent N₂ breakthrough from affecting recovery, the CO₂-N₂ combination flooding is studied by using an ideal homogeneous model.

According to the formation fluid parameters of oil field, an ideal homogeneity model was established by CMG reservoir numerical simulation software for simulation research. Among them, crude oil composition C₁+N₂+CO₂ mole fraction 21.03%, C₂-C₆ mole fraction 3.79%, C₇+ mole fraction 75.18%, gas-oil ratio 22.43 m³/m³, original oil saturation 65%, formation crude oil density 803 kg/m³, saturation pressure 4.704 MPa, pressure gradient 0.1 MPa/m. The physical model is shown in Figure 1.

3. Effect of length-thickness ratio on CO₂ flooding recovery

To study the influence of length-thickness ratio of homogeneous model on the maximum slug and recovery of CO₂ flooding, a 3×10⁻⁶ μm² permeability and 10.0% porosity homogeneity model was selected. 4×16×100 grids were placed on the models with thickness 1 cm, width 4 cm and different lengths. The maximum effective slug and recovery were calculated with continuous CO₂ injection in different length-thickness ratio models by changing the model length. The results are shown in Figure 2.
It can be seen from Figure 2 that, in general, the recovery of different length-thickness ratio models increases with the increase of CO₂ slug, and remains unchanged after reaching the maximum. At the same slug, with the increase of length-thickness ratio, the recovery of the model increased, when the length-thickness ratio reached 100, the recovery was less affected by length-thickness ratio and there was no significant difference.

According to Figure 2, curve of CO₂ maximum injection slug and recovery can be obtained. The results are shown in Figure 3 and Figure 4.

As can be seen from Figure 3, when the length-thickness ratio is under the 100, the maximum CO₂ injection slug increased with the increases of the length-thickness ratio. When the length-thickness ratio is 100, the maximum CO₂ injection slug reaches 1.0, and then the maximum injection slug has a small change and tends to be stable.

As can be seen from Figure 4, when the model length-thickness ratio is under the 100, the recovery increased with the increase of the length-thickness ratio. When the length-thickness ratio is 100, the recovery increased slightly, and the recovery was 72.42%. After that, the recovery tends to be stable and does not increase with the increase of length-thickness ratio. Considering that length-thickness ratio of actual reservoir in an oilfield is about 30, the recovery is 43.97%.

In conclusion, when the model length-thickness ratio is less than 100, the length-thickness ratio has a great influence on the maximum injection slug and the recovery. When the length-thickness ratio is equal to 100, the maximum injection slug reaches the maximum and the recovery increase slightly. When the length-thickness ratio is greater than 100, the recovery basically tends to be stable, while the maximum injection slug decrease then changed little after the length-thickness ratio is equal to 200. Therefore, the single oil layer thickness less than 1% of the well spacing is more conducive to improve
the recovery.

The result shows that when the model length-thickness ratio is under the 100, CO₂ breakthrough the oil easily in the process of displacement, so the contact time with crude oil is short and it is not easy to achieve miscibility, resulting in low displacement efficiency and low recovery. With the increase of length-thickness ratio, the contact time between CO₂ and crude oil gradually increases, and more CO₂ can form miscibility with crude oil, so the displacement efficiency increases and the recovery increases. When the length-thickness ratio is greater than 100, the formation takes the shape of long and slim tubes, the miscible zone of CO₂ and crude oil is basically stable, and the recovery is also stable.

4. Effect of combination flooding slug on input-output ratio

In order to obtain high recovery and reduce injection cost, the effect of CO₂ slug on input-output ratio in CO₂-N₂ combination flooding was studied. Due to the high cost of gas flooding, it is necessary to determine the maximum injection of CO₂ slug to obtain the optimal input-output ratio from the economic view. Considering the fact that the actual reservoir length-thickness ratio of the oilfield is about 30, a 30 cm long, 4 cm wide and 1 cm thick model is selected to calculate the recovery of CO₂ slug in CO₂-N₂ combination flooding when the injection of CO₂ slug was 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.40 and 0.50, respectively, and then the relationship curve between the recovery of combination flooding and the injection of CO₂ slug is made. The results are shown in Figure 5.

Figure 5 shows that the recovery of combination flooding increases with the increase of CO₂ slug. When slug reaches 0.3 PV, the recovery is 43.41%. Since then, the recovery is less affected by slug and has no obvious change. It shows that when the slug is less than 0.3, the injected CO₂ can be completely dissolved in crude oil and miscible with crude oil, and all play the role of oil displacement. Therefore, the recovery increases with the increase of the number of CO₂ slug. When the slug is greater than 0.3, the CO₂ injected first is in full contact with the crude oil, extracts the light hydrocarbon components in the crude oil, achieves miscibility, and forms the "oil wall", leaving the heavy hydrocarbon components behind the oil wall. The injected CO₂ was exposed to more heavy hydrocarbon components and less light hydrocarbon components, the injected CO₂ could not play its due role, so the recovery did not increase significantly after slug was greater than 0.3.

In order to determine the influence of CO₂ slug in CO₂-N₂ combination flooding on input-output ratio, the input-output ratio of different CO₂ and N₂ slug injected into CO₂-N₂ combination flooding was calculated based on the recovery data of different slug combinations in Table 1. The relevant parameters are: the price of liquid CO₂ is ¥435/t, N₂ price under standard condition is ¥1.47/m³, the international crude oil price is $70/ bbl (the exchange rate between dollar and RMB is 6.868). Under this model, the formation crude oil volume factor is 1.10 and the original oil saturation is 65%.

The calculation results are shown in the Figure 6 when only CO₂ and N₂ injection cost and oil production revenue are considered.

### Table 1. Recovery of different slugs combinations.

| Injected slug (PV) | CO₂ | 0.05 | 0.1 | 0.15 | 0.2 | 0.25 | 0.3 | 0.4 | 0.5 |
|-------------------|-----|------|-----|------|-----|------|-----|-----|-----|
|                   | N₂  | 0.24 | 0.23 | 0.22 | 0.18 | 0.21 | 0.22 | 0.15 | 0.4 |
| Ultimate Recovery |     | 0.29 | 0.33 | 0.37 | 0.38 | 0.46 | 0.52 | 0.55 | 0.54 |
| Recovery (%)      |     | 27.68 | 32.95 | 36.52 | 37.92 | 41.12 | 43.41 | 43.99 | 44.02 |
5. Effect of permeability on recovery and input-output ratio of combination flooding

To study the effect of permeability on CO₂-N₂ combination flooding recovery, the permeability models of 3×10⁻³μm², 6×10⁻³μm², 9×10⁻³μm² and 30×10⁻³μm² were selected to calculate the recovery at 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.40, and 0.50 respectively in CO₂-N₂ combination flooding. The results are shown in Figure 7.

As can be seen from Figure 7, the change trend of the relationship curve between CO₂-N₂ combination flooding recovery with different permeability and CO₂ slug injection is basically the same. When the CO₂ slug is small, the recovery increases with the increase of the slug. When the CO₂ slug reaches a certain value, the recovery reaches the maximum and remains stable. Compared with different permeability, as permeability increases, the combination flood recovery of the same CO₂ slug is decreased, and the required CO₂ slug increases when the combination flooding reaches the recovery. This is because, under the same CO₂ slug, the lower the permeability, the weaker the fingering phenomenon of CO₂ in crude oil, the more favorable in the miscibility of CO₂ and crude oil, and the higher the displacement efficiency of combination flooding. Therefore, the 3×10⁻³μm² permeability model has always been higher than the other three permeability models.

According to the data in Figure 7, the oil recovery and input-output ratio of different CO₂ slugs +N₂ slugs in CO₂-N₂ combination flooding with four permeability was calculated, as shown in Figure 8.
Figure 7. Recovery curves with different permeability.

Figure 8. Input-output ratio curves with different permeability.

As can be seen from Figure 8, the input-output ratio of CO₂-N₂ combination flooding with different permeability has basically the same change trend, showing an inverted “S” curve. When CO₂ slug is small (PV < 0.2), the input-output ratio does not change with the increase of slug and remains stable at the maximum. When the CO₂ slug reaches a certain value (PV ≥ 0.2), the input-output ratio decrease then remains stable after it reaches the minimum value. Compared with different permeability, the combination flooding input-output ratio of the 9×10⁻³μm² permeability is always the maximum when CO₂ slug is less than 0.2 PV. When CO₂ slug is greater than or equal to 0.2 PV, there is no significant difference in the input-output ratio of each permeability models.

While the CO₂ slug is smaller than 0.2 PV, the permeability model of 9×10⁻³μm² has a lower recovery, but its injection slug is also lower than the others. Thus, compared with the other three kinds of permeability, the reduction ratio of the total price of crude oil produced is lower than that of the total price of injected gas, so the 9×10⁻³μm² permeability model has the highest input-output ratio. After injecting CO₂ slug greater than 0.2 PV, four kinds of permeability of the combination flooding recovery and eventually injected slug has no obvious difference, thus the input-output ratio of each permeation rate is substantially the same.

The reasonable size of CO₂ slug in the CO₂-N₂ combination flooding of homogeneous model is affected by the comprehensive factors such as reservoir permeability, length-thickness ratio, and the price of crude oil, CO₂ and N₂, etc., which shall be determined according to the specific situation.

6. Conclusion
(1) When the length-thickness ratio of oil layer is less than 100, the recovery increases with the increase of length-thickness ratio of the model and the recovery tends to be stable after the length-thickness ratio reaches 100. Therefore, the single oil layer thickness less than 1% of the well spacing is more conducive to improving the recovery.

(2) In actual oil reservoirs with a lengthen-thickness ratio of 30, the slug composition of CO₂-N₂ combination flooding should be 0.3 PV CO₂ slug + subsequent N₂.

(3) With the increase of permeability, the composite flooding recovery of the same CO₂ slug decrease, and the required CO₂ slug increases when the composite flooding reaches the ultimate recovery. So, the lower the permeability is, the more favorable it is for the CO₂-N₂ combination flooding.

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