Gas Slug Compound Flooding in Low and Ultra-low Permeability Layer

Taoping Chen*, Wen Sun, Jiaqi Bi, Bin Zhao and Ru He
Enhanced Oil and Gas Recovery Key Laboratory of Ministry of Education, Northeast Petroleum University, Daqing, Heilongjiang, 163318, China
*Taoping Chen’s e-mail: ctp010@nepu.edu.cn

Abstract. In order to improve the recovery of gas slug compound flooding in low permeability and ultra-low permeability reservoirs, two methods of the carbon dioxide-nitrogen and the rich gas-nitrogen compound flooding are studied. The results show that in low permeability and ultra-low permeability reservoirs, the use of a single injection of a reasonable pre-slug (carbon dioxide or rich gas) + subsequent nitrogen slug compound flooding can reduce the size of the pre-slug, give full play to the advantages of both the pre-slug and nitrogen, and obtain a better flooding efficiency. Under the same conditions, the recovery of the ultra-low permeability cores used in this experiment is 7.6% higher than the recovery of the low permeability cores on average. However, since the reasonable size of the rich gas pre-slug is 0.6 PV, twice as much as the reasonable size of the carbon dioxide pre-slug, and the price of unit volume of the rich gas slug is 1.82 times as much as the price of the carbon dioxide slug under the condition of injection, the final input-output ratio of the carbon dioxide-nitrogen compound flooding is 2.0~2.69 times as much as that of the rich gas-nitrogen compound flooding.

1. Introduction
Low-permeability and ultra-low permeability reservoirs occupy a considerable amount in the geological reserves of crude oil in China, and most of these reservoirs are not suitable for water injection but gas injection. Miscible flooding is the first choice for gas injection development, and during the process of miscible flooding CO₂ and hydrocarbon gases are prone to miscible with crude oil and the displacement efficiency is high, which is the most advantageous method to improve the recovery of low permeability ultra-low permeability reservoirs[1][2].

China has carried out a large number of laboratory studies on carbon dioxide flooding technology. The fluid physical parameters in the process of multistage contact of carbon dioxide are calculated by numerical simulation technology in reference[3]. The experiment of carbon dioxide miscible flooding shows that carbon dioxide can form a miscible zone with crude oil under miscible conditions to block carbon dioxide fingerprinting in reference[4]. The curve characteristics of different phases of immiscible, near-miscible, and miscible were analyzed, and a method for determining the near-miscible flooding region was proposed by means of indoor physical simulation in reference[5].

There are also many laboratory studies on hydrocarbon gas flooding technology in China. The characteristics of phase transition and dynamic displacement efficiency during hydrocarbon injection were studied by capillary displacement experiment in reference[6]. An efficient rich gas flooding injection method is proposed to quantitatively optimize the design of each cycle gas slug size, water slug size and total cycle number in reference[7]. The displacement efficiency of hydrocarbon injection gas under pressure above and below bubble point was studied by combining the results of numerical
simulation software and laboratory physics experiments in reference[8]. A hydrocarbon systems phase flash calculation model for evaporate gas flooding and condensate gas flooding is established based on cubic equation of state and flash calculation theory in reference[9]. The effect of scale effect on miscible oil displacement of natural gas is studied in reference[10]. Taking the X fault block in Dagang oilfield as the research object, the effect of depletion development and natural gas flooding development is predicted and compared by using numerical simulation method. The results show that the depletion development can achieve higher recovery factor and better development effect in reference[11].

Other scholars have made comparative analysis on the mechanism, injection mode and problems of different gas flooding EOR technologies in low permeability reservoirs [12]. These studies have enriched the theoretical basis of gas flooding development in low permeability and ultra-low permeability reservoirs.

At present, due to the restriction of gas source, carbon dioxide flooding or gas-rich flooding cannot be widely applied in China. Compared with carbon dioxide and rich gas, nitrogen gas source is relatively abundant, but its miscibility pressure with crude oil is high, so it is difficult to achieve miscibility in practice. It is mainly based on elastic displacement with limited displacement efficiency [13]. In this regard, the method of developing low permeability reservoir by partially replacing carbon dioxide with nitrogen is proposed, because it can achieve the purpose of saving carbon dioxide and improving recovery [14][15]. Due to the diffusion and dispersion between the subsequent nitrogen and the pre-gas slug, in order not to affect the miscibility between the pre-gas slug and the crude oil, the pre-gas slug needs to have sufficient length. Therefore, studies have been carried out on carbon dioxide-nitrogen compound flooding and rich gas-nitrogen compound flooding in low permeability and ultra-low permeability reservoirs, to explore how to give full play to the advantages of carbon dioxide, rich gas and nitrogen to achieve the purpose of effectively improving the recovery on the basis of reducing the consumption of carbon dioxide or rich gas.

2. Physical model experiment
In order to determine the reasonable pre-slug size and oil displacement effect in gas slug compound flooding, two kinds of natural cores, low permeability and ultra-low permeability cores, were used to carry out the experiments of carbon dioxide-nitrogen compound flooding and rich gas-nitrogen compound flooding.

2.1. Experimental materials

2.1.1. Core
In order to study the effect of carbon dioxide-nitrogen compound flooding and rich gas-nitrogen gas compound flooding oil displacement in the actual layer, natural cores should be used in physical model experiments. To this end, 24 kinds of natural core samples were screened for permeability test. According to the permeability test data and the results of comparing actual reservoir properties, the No.13 low permeability core and the No.6S ultra-low permeability core were selected as the natural cores for physical model experiment. Core size is length 30 cm × width 4.5 cm × thickness 1.3 cm. The average effective permeability and average porosity of low permeability core is \(1.732 \times 10^{-3} \mu \text{m}^2\) and 20.57%. The average effective permeability and average porosity of ultra-low permeability core is \(2.35 \times 10^{-3} \mu \text{m}^2\) and 20.42%.

2.1.2. Oil, gas and water
The experimental crude oil is the simulated oil from well S99-TX13 of YS oilfield. The original dissolved gas-oil ratio is 22.3 m³/m³, and the saturation pressure is 4.704 MPa. At 90°C, the formation oil density is 807.2 kg/m³, the formation oil viscosity is 3.756 mPa.s, and the minimum miscible pressure of carbon dioxide-crude oil is 25.9 MPa. The composition of the rich gas is shown in Table 1.
The minimum miscible pressure of the rich gas-crude oil is 27.4 MPa. The saturated water is used to simulate the original formation water with a salinity of 6778 mg/L.

Table 1. The composition of the rich gas

| Component | Volume fraction (%) |
|-----------|--------------------|
| N₂        | 1.808              |
| CO₂       | 0.404              |
| CH₄       | 85.560             |
| C₂-C₄     | 12.190             |
| C₅        | 0.038              |

2.2. Scheme and equipment

There are 5 displacement schemes for carbon dioxide-nitrogen compound flooding and rich gas-nitrogen compound flooding respectively (see Table 2 for details). During the experiment, oil production and gas production were recorded in real time and the experiment would end until the gas-oil ratio of the produced fluid reached more than 1500 mL/mL. The displacement experiment was carried out under constant temperature and pressure. The experiment temperature is 90°C, and the outlet back pressure is 28.60 MPa, so as to ensure the complete miscible state of carbon dioxide-crude oil or gas rich-crude oil.

The displacement experiment equipment is HBCD-70 high temperature and high pressure core displacement device which has constant pressure and constant speed metering pump, special high temperature and high pressure core holder, oil-gas-water three phase metering system, computer control system, etc., meeting the requirements of the experiment plan.

2.3. Results analysis

Low-permeability and ultra-low permeability cores were selected for studying five displacement schemes respectively. The recovery results of different cores and displacement schemes with carbon dioxide-nitrogen compound flooding and rich gas-nitrogen compound flooding are shown in Table 2.

Table 2. The result of gas slug compound flooding

| Flooding scheme | Low-permeability | Ultra-low permeability | Flooding scheme | Low-permeability | Ultra-low permeability |
|-----------------|------------------|-----------------------|-----------------|------------------|-----------------------|
|                 | Core No. | Recovery (%) | Core No. | Recovery (%) | Core No. | Recovery (%) | Core No. | Recovery (%) |
| Full N₂        | 1312     | 17.15       | 6S2     | 35.27         | 1312     | 17.15       | 6S2     | 35.27         |
| 0.1PV CO₂+N₂   | 1313     | 34.18       | 6S3     | 55.61         | 1325     | 31.78       | 6S18    | 56.42         |
| 0.2PV CO₂+N₂   | 1314     | 47.04       | 6S5     | 63.92         | 1323     | 47.46       | 6S19    | 64.69         |
| 0.3PV CO₂+N₂   | 1315     | 61.41       | 6S8     | 69.37         | 1324     | 65.91       | 6S20    | 73.21         |
| Full CO₂       | 1310     | 61.87       | 6S1     | 71.59         | 1322     | 63.92       | 6S17    | 74.10         |

As can be seen from table 2, two kinds of gas slug compound flooding recovery are much higher than the full nitrogen flooding recovery, which indicates carbon dioxide or rich gas pre-slug play the advantages of themiscible displacement. In the compound gas slug flooding, the ultra-low permeability core can achieve better displacement effect compared with the low permeability core. The final recovery of the two kinds of cores with CO₂ pre-slug +N₂ flooding differs by 7.96%, and that of the two kinds of cores with rich gas pre-slug +N₂ flooding differs by 7.30%.
3. Numerical simulation

The CMG reservoir numerical simulation software was used to build a three-dimensional model that was exactly the same size as the natural core used in the experiment. The model size is 30 cm long × 4.5 cm wide × 1.3 cm high, grid division \(i \times j \times k\) is 120×18×4 and grid step size is 0.25 cm. In order to simulate the actual situation of the injection and production end of the experiment core, the two layers of grids on the injection and production end face were combined, and the three-dimensional grid of the experimental model was shown in Figure 1.

The core parameters are the average value of the natural core used in the experiment. Crude oil consists of the following components: \(C_1+N_2+CO_2\) content is 21.21%, \(C_2-C_6\) content is 2.82% and \(C_7^+\) content is 75.97%. The original oil saturation is 65%, and the other property parameters were the same as the physical model experiment.

![Figure 1. Three dimensional grid of experimental model](image1)

The theoretical curves of recovery and pre-slug size for different gas slug compound flooding injection schemes of low permeability and ultra-low permeability core were calculated by CMG reservoir numerical simulation software, and the numerical simulation model theoretical recovery curve and the physical model oil displacement experiment results were drawn in the same figure, as shown in Figure 2.

![Figure 2. Relation curve between recovery and gas pre-slug size](image2)
It can be seen from Figure 2(a) and Figure 2(b) that the numerical simulation result of the physical model used in the experiment is consistent with the overall trend of the experimental data. That is to say, the physical model recovery with different CO₂ PV number is similar to that of numerical model, only small difference between them. That is, with the size of the CO₂ pre-slug increasing, the recovery of the CO₂ pre-slug + N₂ compound flooding increases continuously. When the CO₂ pre-slug size is about 0.3PV, a better oil displacement effect can be achieved. The recovery is close to that of full CO₂ flooding. With the increase of CO₂ pre-slug size the recovery of CO₂ pre-slug + N₂ compound flooding tends to be stable.

By the figure 2(c), figure 2(d), numerical simulation results of the physical model used in the experiment are in good agreement with the experimental data, and with the increase of rich gas injection, rich gas pre-slug + nitrogen displacement compound flooding recovery constantly increases. When the injection volume of rich gas is about 0.6PV, a better effect can be achieved. The recovery of rich gas pre-slug + nitrogen compound flooding is similar to that of full gas rich flooding. Therefore, in gas rich and nitrogen compound flooding, 0.6PV is appropriate for rich gas slug size.

4. Comparison between two kinds of compound flooding

The comparative study of carbon dioxide-nitrogen compound flooding and rich gas-nitrogen compound flooding is carried out from two aspects of main technical index and economic index.

4.1. Technical index

For the convenience of comparison, the low-permeability and ultra-low permeability core experimental curves of carbon dioxide-nitrogen compound flooding and rich gas-nitrogen compound flooding are drawn in the same figure, as shown in figure 3.

![Comparison of the gas slug compound flooding recovery relationship curves](image)

As can be seen from Figure 3, under the same pre-slug size, the recovery of the compound carbon dioxide-nitrogen flooding is always higher than that of the compound rich gas-nitrogen flooding. Under the same recovery, the pre-slug PV number of rich gas is always higher than that of carbon dioxide. The final recovery of the rich gas-nitrogen compound flooding is about 4% higher than that of the carbon dioxide-nitrogen compound flooding, but the required rich gas pre-slug PV number is twice as much as that of the carbon-dioxide.

The analysis shows that the minimum miscibility pressure of CO₂ (25.9MPa) is lower than the minimum miscibility pressure of rich gas (27.4MPa). Under the same injection pressure (30.2MPa), the solubility of CO₂ is stronger and the miscibility zone is easier to form than that of rich gas. In addition, with the same PV number of the pre-slug injected, CO₂ is liquid under displacement pressure and has a high density, and its total mass is much higher than that of rich gas under displacement pressure. Therefore, the recovery of compound carbon dioxide-nitrogen flooding is higher than that of rich gas-nitrogen compound flooding.
4.2. Economic index

In order to determine the impact of gas pre-slug of compound flooding on the injection gas-production oil ratio (IGPOR, the volume of oil produced by injecting standard condition 1 m³ gas pre-slug) and the per ton oil gas cost (PTOGC, the total cost of producing 1 t crude oil), according to the data in Table 2, the injection gas-production oil ratio and the per ton oil gas cost are calculated in the low permeability and ultra-low permeability core rich gas-nitrogen compound flooding and carbon dioxide-nitrogen compound flooding with different size of gas pre-slug. The relevant parameters are: The price of rich gas in standard condition is ¥2.28 /m³. The price of liquid CO₂ is ¥435/ton, which is ¥0.87/m³ in standard condition. Under standard condition, the price of N₂ is ¥1.47/m³. International crude oil price is $50/barrel (USD to RMB exchange rate: 7.0). Under the condition of this model, the formation crude oil volume coefficient is 1.10 and the original oil saturation is 65%. The comparison curve between the injection-production oil-gas ratio and the gas cost of per ton oil based on the calculation results is shown in Figure 4 and Figure 5.

As can be seen from Figure 4, in the low permeability core, when the PV number of the pre-slug is same, the injection-production oil-gas ratio of the compound flooding with carbon dioxide-nitrogen is higher than that of the compound flooding with rich gas-nitrogen. Since the PV number of N₂ in the two kinds of compound flooding is small and basically the same. Therefore, the injection gas-production oil ratio of carbon dioxide-nitrogen compound flooding with high recovery is greater than that of rich gas-nitrogen compound flooding with low recovery. The reasonable slug size of carbon dioxide in the carbon dioxide-nitrogen compound flooding is 0.3 PV. In this case, the injection gas-production oil ratio is 4.70×10⁻³, and the per ton oil gas cost is ¥780.83. The reasonable slug size of
rich gas in rich gas-nitrogen compound flooding is 0.6 PV. At this time, the injection gas-production oil ratio is 2.97×10^{-3}, and the per ton oil gas cost is ¥935.58. In the case of reasonable slug injection, the injection gas-production oil ratio of carbon dioxide-nitrogen compound flooding is 1.73×10^{-3} larger than that of rich gas-nitrogen compound flooding, and the per ton oil gas cost of carbon dioxide-nitrogen compound flooding is ¥154.75 lower than that of rich gas-nitrogen compound flooding.

As can be seen from Figure 5, in the ultra-low permeability core, with the same PV number of the pre-slug, the injection-production oil-gas ratio of the carbon dioxide-nitrogen compound flooding is lower than that of the rich gas-nitrogen compound flooding. Due to the large PV number of subsequent N2 slug in the carbon dioxide-nitrogen compound flooding (0.3 PV), the PV number of the total injected gas in the carbon dioxide-nitrogen compound flooding is greater than that of the rich gas-nitrogen compound flooding, which weakens the effect of the carbon dioxide-nitrogen compound flooding recovery higher than that of the rich gas-nitrogen compound flooding recovery. Therefore, the injection-production oil-gas ratio of carbon dioxide-nitrogen compound flooding is lower than that of rich gas-nitrogen compound flooding. The reasonable slug size of carbon dioxide in the carbon dioxide-nitrogen compound flooding is 0.3 PV. In this case, the injection gas-production oil ratio is 3.16×10^{-3}, and the per ton oil gas cost is ¥467.01. While the reasonable slug size of rich gas in rich gas-nitrogen compound flooding is 0.6 PV. At this time, the injection gas-production oil ratio is 3.23×10^{-3}, and the per ton oil gas cost is ¥857.26. In the case of reasonable slug injection, the injection gas-production oil ratio of carbon dioxide-nitrogen compound flooding is 0.07×10^{-3} less than that of rich gas-nitrogen compound flooding, and the per ton oil gas cost of carbon dioxide-nitrogen compound flooding is ¥390.25 lower than that of rich gas-nitrogen compound flooding.

Taking the different pre-slug size into consideration, subsequent nitrogen slug size is also different. Then the input-output ratio (IOR, the ratio of the total price of produced crude oil to the total cost of injected gas) of the carbon dioxide-nitrogen compound flooding and rich gas-nitrogen flooding in different cores are calculated when the cost of the injected gas is considered only, and draw the corresponding curve is shown in figure 6.

![IOR Comparison](image)

**Figure 6. Comparison of IOR relationship curves in low and ultra-low permeability core**

As can be seen from Figure 6, in the same core, the input-output ratio of the carbon dioxide-nitrogen compound flooding is always higher than that of the rich gas-nitrogen compound flooding under the same PV number pre-slug injected, and the input-output ratio of the final flooding under the reasonable carbon dioxide pre-slug is also higher than that of the final flooding under the reasonable rich gas pre-slug. This is due to the fact that although the final recovery of the rich gas-nitrogen compound is approximately 4% higher than that of the carbon dioxide-nitrogen compound flooding, the PV number of rich gas pre-slug required is twice that of carbon dioxide pre-slug. That is, under the same pre-slug PV number, the recovery of the carbon dioxide-nitrogen compound flooding is always higher than that of the rich gas-nitrogen compound flooding. Moreover, under the condition of injection, the price per unit volume of rich gas is ¥560.17/m³ and the price per unit volume of carbon...
dioxide is ¥307.4/m³. Under the combined factors of the injected slug PV number, recovery and gas price per unit volume, the input-output ratio of the carbon dioxide-nitrogen compound flooding is 2~2.69 times that of the rich gas-nitrogen compound flooding.

5. Conclusions
(1) In the carbon dioxide-nitrogen compound flooding of low permeability and ultra-low permeability reservoir, the compound flooding with 0.3 PV CO₂ slug + N₂ slug can achieve the recovery value of full CO₂ injection. However, when adopting rich gas slug + N₂ slug compound slug flooding, the rich gas slug requires 0.6PV in order to achieve the recovery value of the full rich gas injection.

(2) Compared with the low-permeability core, a better displacement effect can be achieved by adopting the carbon dioxide pre slug + nitrogen compound flooding in ultra-low permeability core. The ultra-low permeability core used in this study has a higher recovery of 7.96% than the low-permeability core. When rich gas slug + N₂ slug compound flooding is used, the recovery of the two kinds of cores differs by 7.30%.

(3) This study belongs to low permeability and ultra-low permeability core completely miscible displacement. While the final recovery of the rich gas-nitrogen compound flooding is 4% higher than that of carbon dioxide-nitrogen compound flooding. However, since the number PV of the injected rich gas is twice as much as that of the injected carbon dioxide, and the price per unit volume of rich gas under injected conditions is 1.82 times that of carbon dioxide, so the final input-output ratio of carbon dioxide-nitrogen compound flooding is 2.0~2.69 times that of rich gas-nitrogen compound flooding.

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References
[1] Shen P.P. (2006) Enhanced recovery technology. Petroleum Industry Press. Beijing.
[2] Deng R.J., Wu Y.C., Chen D.B., et al. (2003) Hydrocarbon gas injection technology for low permeability reservoir. Petroleum Industry Press. Beijing.
[3] Su C., Sun L., Li S.L. (2001) Mechanism of CO₂ miscible flooding during multiple contact procedure. Journal of Southwest Petroleum University (Science & Technology Edition), 23(2): 33-36.
[4] Li M.T., Shan W.W., Liu X.G., et al. (2006) Laboratory study on miscible oil displacement mechanism of supercritical carbon dioxide . Acta Petrolei Sinica, 27(3): 80–83.
[5] Zhao F.L., Zhang M., Hou J.R., et al. (2018) Determination of CO₂ miscible condition and near-miscible region flooding in low permeability reservoir. Oilfield Chemistry, 35(2): 273-277.
[6] Lai F.P., Li Z.P., Yang Z.H., et al. (2014) The study of components mass transfer mechanism and the rules of fluid phase alteration in the process of hydrocarbon gas drive. Journal of Natural Gas Science and Engineering, 21: 411-416.
[7] Wang S.K., Zhang W.D., Yuan X.C., et al. (2016) New WAG injection model based on the produced gas Density variation for enriched-gas flooding. Journal of Southwest Petroleum University (Science & Technology Edition), 38(3): 95-100.
[8] Xu Q.H. (2017) The mechanism and characteristic study of the gas miscible flooding in donghetang oil reservoir. Southwest Petroleum University. Chengdu.
[9] Xu Q. (2017) Modeling and analysis of the change of the equilibrium compositions in vaporizing-and condensing-gas drive processes. Petroleum Geology and Recovery Efficiency, 24(04): 99-104.
[10] Yang X. (2018) Influence of scale effect on oil displacement efficiency by natural gas miscible-flooding. Reservoir Evaluation and Development, 8(05): 37-41.
[11] Zhang Y., Cheng H.Y., Liu M. (2019) Minimum miscibility pressure and phase behavior of natural gas flooding in deep-seated and low permeability fault-block reservoir. Science Technology and Engineer, 19(11): 96-102.
[12] Zhen C.Y., Fan J.Y., Wang W., et al. (2014) Comparison of different gas flooding enhanced oil recovery techniques in low permeability reservoirs. China Science and Technology Information, 26(S2): 79-80.
[13] Wang J.A., Yue L., Yuan G.J., et al. (2004) Laboratory research on N$_2$ drive. Petroleum Exploration and Development, 31(3): 119-121.
[14] Sun Y., Du Z.M., Sun L., et al. (2012) Mechanism research of enhancement oil recovery by CO$_2$ pushed by N$_2$. Journal of Southwest Petroleum University (Science & Technology Edition), 34(3): 89-96.
[15] Chen T.P., Zhao B., He R. (2018) CO$_2$ and N$_2$ flooding methods in ultra-low permeability oil reservoir. Petroleum Geology and Oilfield Development in Daqing, 37(4): 127-132.