

The optimization of pre-slug size in CO₂-N₂ compound flooding

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Abstract. In order to enhance oil recovery in low and ultra-low permeability layer, both of the numerical simulation and physical model experiment have been researched. First, the dynamic distribution of CO₂ and N₂ in the oil and gas phase in the CO₂-N₂ compound flooding process was numerically simulated by using the long slim-tube model. The results show that the CO₂ slug should have at least 0.3 PV to prevent the impact of N₂ channeling effectively. Second, under the experimental conditions of complete miscibility of CO₂-crude oil, the two types of natural cores including low and ultra-low permeability, respectively, are used for experimental study on oil displacement. The results confirm that CO₂-N₂ compound flooding with 0.3 PV CO₂ pre-slug can achieve a good result. Finally, a five-point well pattern element model is established by CMG. The recovery and the gas cost of per ton of oil are calculated respectively for CO₂-N₂ compound flooding and full CO₂ flooding at 300 m well spacing of low and ultra-low permeability layer. According to the simulation results, the optimal CO₂ pre-slug size in CO₂-N₂ compound flooding under the condition of low and ultra-low permeability layer five-point well pattern is 0.4 PV.

1 Introduction

Most of low permeability and ultra-low permeability layers can not be effectively developed by water flooding. So applying gas flooding, specially, CO₂ flooding to develop low permeability and extra low permeability reservoirs has become a focus of EOR technology.

In recent years, scholars at home and abroad have done a lot of researches and experiments on CO₂ flooding. Basic theories such as factors affecting CO₂ flooding efficiency^[1], miscible flooding mechanism^[2,3], flow in a porous medium characteristics of CO₂ flooding^[4], and determination of near-miscible flooding region^[5] have been explored. The factors affecting the minimum miscibility pressure of CO₂-crude oil^[6] and the determination method of the minimum miscibility pressure^[7] were studied. The long core physical model experiment of CO₂ miscible flooding^[8], the CO₂ flooding experiment of ultra-low permeability-tight reservoir and so on^[9] were carried out in laboratory. By using reservoir numerical simulation technology, the CO₂ flooding simulation calculation under non-darcy flow condition^[10] was carried out, etc., and the CO₂ miscible flooding scheme and development mode were optimized^[11]. These studies provide a theoretical basis for CO₂ flooding technology.

The carbon dioxide flooding pilot test had achieved a good effect in Jilin and other oil fields. Because of the shortage of carbon dioxide, it can not be used widely. The references^[12,13] point that using carbon dioxide as the first slug then injecting nitrogen can improve the oil recovery and save the carbon dioxide amount. In order to

avoid that diffusion and dispersion between CO₂ and N₂ effects miscible phase between CO₂ and crude oil, the CO₂ pre-slug should be long enough. Therefore, the ultra-low permeability reservoir in the YS oilfield is taken as the background. Numerical simulation and physical model experiments of CO₂-N₂ compound flooding in low permeability and ultra-low permeability reservoir are carried out. The size of CO₂ pre-slug in CO₂-N₂ compound flooding is optimized to improve the oil recovery.

2 The mechanism analysis in long slim-tube model

On the basis of formation and fluid parameters of YS oilfield, the long slim-tube ideal model was established by using CMG reservoir numerical simulation software. The size of the model is 40 cm long × 4.5 cm wide × 4.5 cm high and its grid division is 40×1×1. The permeability and porosity of the model are 1.06×10⁻³μm² and 10.65%. Crude oil consists of the following components: C1+N₂+CO₂ content is 21.21%, C₂-C₆ content is 2.82% and C₇+ content is 75.97%. The original dissolved gas-oil ratio is 22.3 m³/m³ and the saturation pressure is 4.704 MPa. At the formation temperature of 90°C, the formation oil density is 807.2 kg/m³ and the formation oil viscosity is 3.756 mPa·s. The minimum miscible pressure of CO₂ and crude oil is 25.9 MPa.

In order to analyze the mechanism of CO₂-N₂ compound flooding clearly, the dynamic distribution of CO₂ and N₂ in the oil and gas phase in the CO₂-N₂

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compound flooding process was numerically simulated by using the long slim-tube model, and the results are shown in Fig. 1. In Fig. 1, the dimensionless distance 0 is the injection end and the dimensionless distance 1 is the extraction end.

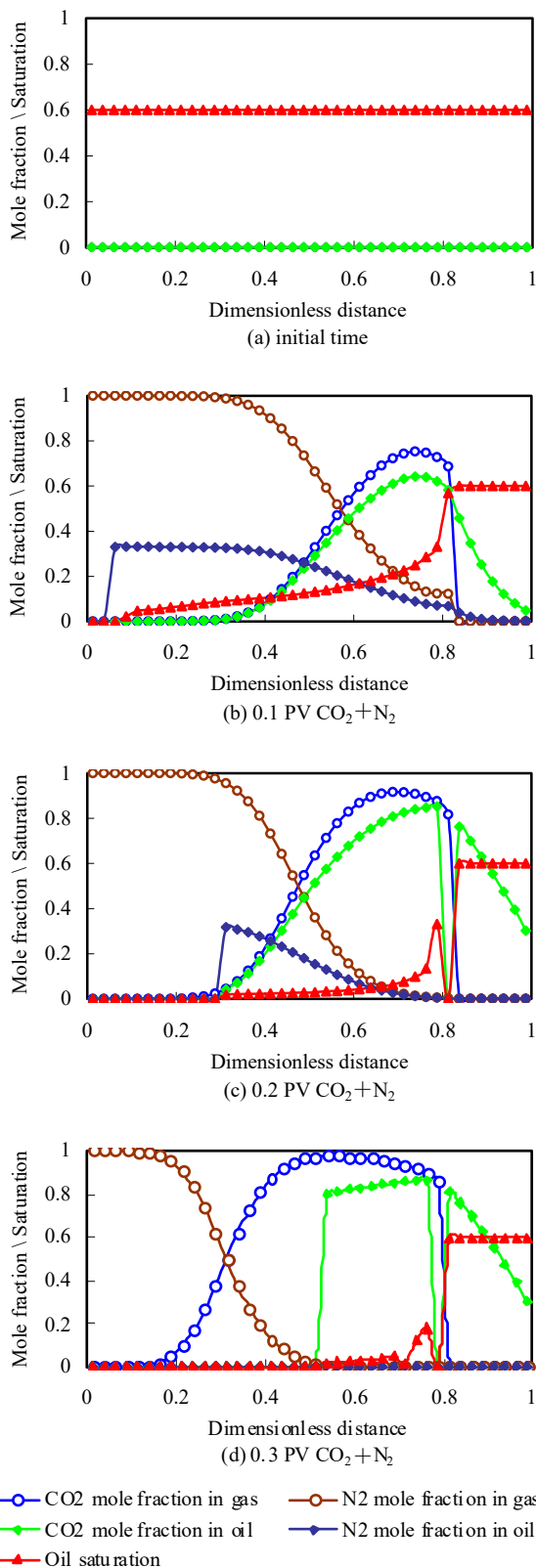


Fig. 1. Dynamic distribution of CO₂ and N₂ in hydrocarbon phase by CO₂-N₂ compound flooding

Fig. 1 shows the dynamic distribution of CO₂ and N₂ in oil and gas phases at the initial stage and 0.1 PV CO₂+N₂, 0.2 PV CO₂+N₂, and 0.3 PV CO₂+N₂ three displacement schemes while the cumulative injection amount is 0.5 PV by CO₂-N₂ compound flooding. In Fig. 1 (b), (c) As it be seen in large range (dimensionless distance is about 0.3~0.8), in the gas phase, N₂ and CO₂ is the form of mixture, and in the oil phase, the N₂ molar content is higher, direct contact with mixed phase front, which suggests that 0.1~0.2 PV CO₂ slug cannot effectively isolate N₂ influence on CO₂ miscible displacement leading edge, thus the recovery is not high. Fig. 1(d) shows the distribution of CO₂ and N₂ in the oil and gas phases when the CO₂ slug injection amount is 0.3 PV and cumulative injection amount is 0.5 PV (near the end of displacement). It can be clearly seen from Fig. 1(d) that the dimensionless range of 0.2 is pure N₂ region. Mixed gas region of N₂ and CO₂ is the range of 0.2~0.7. The range of 0.7~1.0 is CO₂ region which only contains a very small amount of N₂. Near 0.8 is miscible front. The content of N₂ mole in 0.8~1 oil phase is very low. The above indicates that 0.3 PV CO₂ slug effectively isolated the influence of N₂ on CO₂ miscible displacement leading edge. Therefore, it can be concluded that when the CO₂ injection volume is less than 0.3 PV, N₂ breaks through the CO₂ slug and contacts the crude oil, affecting the miscibility of CO₂ and the crude oil, thereby affecting the recovery. When the CO₂ injection volume is 0.3 PV, the CO₂ slug has an effective blocking effect on N₂ inrush and reduces the influence of N₂ on the CO₂ miscible front. Subsequently, N₂ acts as a propellant to maintain formation pressure and play the role of elastic displacement, so the recovery is higher.

In essence, due to the diffusion and dispersion between CO₂ and N₂, as well as the differences in density and viscosity between CO₂ and oil phase, mixed zone inevitably exists in the process of CO₂ pre-slug and N₂ displacement. Therefore, from the effect of enhancing recovery, the CO₂ pre-slug must be able to form a stable intermediate band to avoid the channeling of N₂ mixed with CO₂ getting to the CO₂ miscible leading edge. The dynamic distribution of hydrocarbon phase during displacement shows that too small CO₂ slug cannot prevent the impact of N₂ channeling on the miscible flooding, and the CO₂ slug should have at least 0.3 PV to effectively prevent the impact of N₂ channeling.

3 The experiment of natural core

In order to determine the optimal size of CO₂ pre-slug in CO₂-N₂ compound flooding and its oil displacement effect, two kinds of natural cores which named low permeability core and ultra-low permeability core were used to carry out CO₂-N₂ experimental research.

3.1 Experimental materials and program

3.1.1 Experimental materials

Natural core: the core size is 30 cm long × 4.5 cm wide × 4.5 cm high. The average effective permeability and average porosity of low permeability core are $17.91 \times 10^{-3} \mu\text{m}^2$ and 21.49%. The average effective permeability and average porosity of ultra-low permeability core are $2.26 \times 10^{-3} \mu\text{m}^2$ and 20.68%.

Saturated water: simulated original formation water with salinity of 6778 mg/L.

Saturated oil: the original dissolved gas-oil ratio was 22.3 m³/m³ in the simulated oil of well S99-TX13 in YS oilfield. At the temperature of 90°C, the oil density is 807.2 kg/m³ and the oil viscosity is 3.756 mPa·s.

3.1.2 Experimental installation

HBCD-70 High temperature and high pressure core displacement devices include: constant pressure and constant speed metering pump, special high temperature and high pressure core holder, oil, gas and water three-phase metering system, computer control system, etc.

3.1.3 The Experimental scheme

The displacement experiment was conducted under constant temperature and pressure, with the outlet back pressure of 28.60 MPa and the experimental temperature of 90°C.

There are five displacement schemes: N₂ flooding; CO₂ flooding; first inject 0.1, 0.2 and 0.3 PV CO₂, followed by N₂ flooding. During the experiment, oil production and gas production were recorded in real time until the gas-oil ratio of the produced fluid reached 1500 cm³/cm³.

3.2 Experimental results and analysis

Low permeability core and ultra-low permeability core were selected for the experimental study of CO₂ flooding, N₂ flooding, 0.1 PV CO₂+N₂ flooding, 0.2 PV CO₂+N₂ flooding, and 0.3 PV CO₂+N₂ flooding. The relationship between recovery and CO₂ slug size is shown in Fig. 2 and Fig. 3

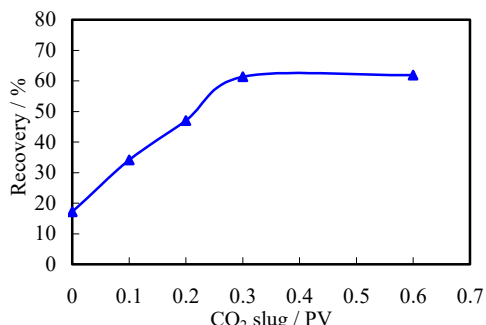


Fig. 2. Relation curve between low permeability core recovery and CO₂ slug size

It can be seen from Fig. 2 and Fig. 3 that with the increase of CO₂ slug size, the recovery of CO₂-N₂ compound flooding increases continuously. When CO₂ pre-slug size is 0.3 PV, higher recovery and a good

effect can be achieved. After CO₂ pre-slug size reaches 0.3 PV, the recovery reaches a high level, then tends to be stable with the increase of CO₂ slug size. It is indicated that the optimal size of CO₂ pre-slug in CO₂-N₂ compound flooding is 0.3 PV.

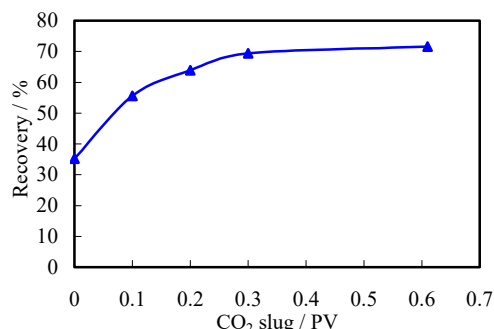


Fig. 3. Relation curve between ultra-low permeability core recovery and CO₂ slug size

By comparison with Fig. 2 and Fig. 3, it can be seen that, compared with low-permeability cores, ultra-low-permeability cores can obtain better displacement effects by adopting CO₂ pre-slug +N₂ compound flooding.

4 The numerical simulation of five-spot well pattern element

The numerical simulation of the ideal long silt-tube model and the natural core physical model experiment both confirm that 0.3 PV CO₂ pre-slug is appropriate for CO₂-N₂ compound flooding in the low permeability and ultra-low permeability layer. Therefore, to determine the slug size of CO₂ and oil displacement effect about CO₂-N₂ compound flooding under the condition of actual oilfield well pattern, it is necessary to carry out numerical simulation research on the five-point well pattern CO₂-N₂ compound flooding in low and ultra-low permeability layer.

4.1 The five-point pattern of low permeability reservoir

The Five-point well pattern model with a distance of 300 m was established in the CMG reservoir numerical simulation software. The permeability and porosity of this model is $30 \times 10^{-3} \mu\text{m}^2$ and 15.5%. The temperature and pressure gradient of this model is 90°C and 0.1 MPa/m. The well bottom pressure of injection well and production well is 40 MPa and 10 MPa. The other rock and hydrocarbon property parameters are the same as the long silt-tube model. The size of the model is 212 m long × 212 m wide × 10 m high and its grid division is $106 \times 106 \times 5$.

According to the limiting gas-oil ratio of 1500 m³/m³ constraint conditions, the recovery of CO₂-N₂ compound flooding with different size of CO₂ slug and full CO₂ flooding are calculated respectively. According to the calculation results, the relation curves between recovery, the gas cost of per ton oil and CO₂ slug size are shown in Fig. 4 and Fig. 5.

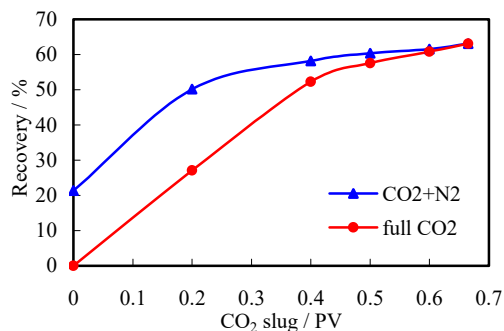


Fig. 4. Relation curve between low permeability reservoir recovery and CO₂ slug size

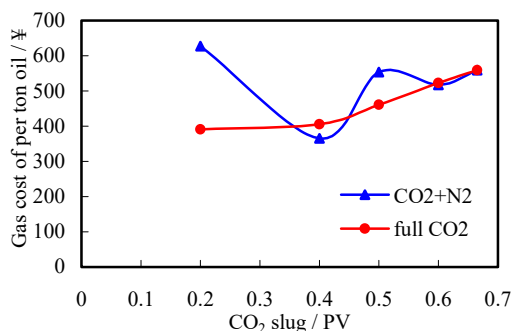


Fig. 5. Relation curve between the low permeability reservoir gas cost of per ton oil and CO₂ slug size

It can be seen from Fig.4, in the five-point pattern of low permeability reservoir, with CO₂ slug size increasing, the recovery of the CO₂-N₂ compound flooding first increases and then remains stable, but the recovery of full CO₂ flooding remains increasing. The recovery of the CO₂-N₂ compound flooding is always higher than the recovery of full CO₂ flooding. The results show that the subsequent injection of N₂ in the CO₂-N₂ compound flooding effectively played the role of replenishing energy. The subsequent injection of N₂ drives the crude oil which is miscible by the pre-slug of CO₂, which improves oil recovery. When the recovery of both is same, the CO₂ slug size required by compound flooding is far lower than that required by full CO₂ flooding. Relative to full CO₂ flooding, CO₂-N₂ compound flooding can not only achieve higher recovery but also reduce CO₂ usage. From the recovery curve of compound flooding, when 0.4 PV CO₂ slug is injected, the recovery of compound flooding begins to level off and approach the final recovery of full CO₂ flooding.

As can be seen from Fig. 5, with the CO₂ slug size increasing, the gas cost curve of per ton oil of CO₂-N₂ compound flooding has a "W" shape in low permeability reservoir five-point well pattern. And the gas cost of per ton oil is the lowest when the CO₂ slug size is 0.4 PV.

Through the analysis of the change of recovery and the gas cost of per ton oil in Fig. 4 and Fig. 5, 0.4 PV CO₂ slug is optimal for CO₂-N₂ compound flooding in low permeability reservoir five-point well pattern. This is because compared with the recovery of 0.6 PV CO₂ slug compound flooding, 0.4 PV CO₂ slug compound flooding reduced recovery by 3.35%, but the usage of CO₂ reduced by 0.2 PV (a third of total amount), which

leads to better flooding benefits. So, the optimal CO₂ pre-slug size of CO₂-N₂ compound flooding is 0.4 PV in the five-point well pattern, and the recovery is 58.19%.

4.2 The five-point pattern of ultra-low permeability reservoir

The permeability and porosity of the five-point pattern of ultra-low permeability reservoir is $3 \times 10^{-3} \mu\text{m}^2$ and 10%. The other parameters are the same as the five-point well pattern model of low permeability reservoir. According to the limiting gas-oil ratio of 1500 m³/m³, the recovery of CO₂-N₂ compound flooding with different CO₂ slug size and full CO₂ flooding are calculated respectively. According to the calculation results, the relation curves between recovery, the gas cost of per ton oil and CO₂ slug size are shown in Fig. 6 and Fig. 7.

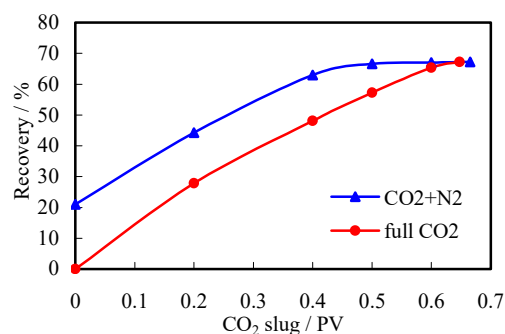


Fig. 6. Relation curve between ultra-low permeability reservoir recovery and CO₂ slug size

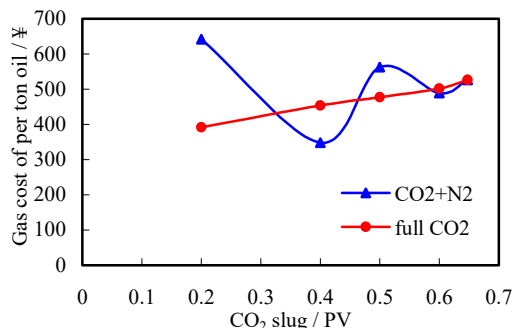


Fig. 7. Relation curve between the ultra-low permeability reservoir gas cost of per ton oil and CO₂ slug size

It can be seen from Fig. 6, in the five-point pattern of ultra-low permeability reservoir, with CO₂ slug size increasing, the recovery of the CO₂-N₂ compound flooding first increases and then remains stable, and the recovery of full CO₂ flooding remains increasing. The recovery of the CO₂-N₂ compound flooding is always higher than the recovery of full CO₂ flooding. When the recovery of both is same, the CO₂ slug size required by compound flooding is far lower than that required by full CO₂ flooding. From the recovery curve of compound flooding, when 0.4 PV CO₂ slug is injected, the recovery of compound flooding begins to level off and approach the final recovery of full CO₂ flooding.

As can be seen from Fig. 7, with the CO₂ slug size increasing, the gas cost curve of per ton oil of CO₂-N₂ compound flooding has a "W" shape in ultra-low

permeability reservoir five-point well pattern. And the gas cost curve of per ton oil is the lowest when the CO₂ slug size is 0.4 PV.

Through the analysis of the change of recovery and the gas cost curve of per ton oil in Fig. 6 and Fig. 7, 0.4 PV CO₂ pre-slug is optimal for CO₂-N₂ compound flooding in ultra-low permeability reservoir five-point well pattern. And the recovery is 62.98%.

It should be pointed out that the pressure at the production end of the laboratory core oil flooding experiment is higher than the minimum miscibility pressure of CO₂ and crude oil, so it belongs to complete miscibility displacement. Under the condition of well pattern, the injection well pressure is much higher than the minimum miscibility pressure of CO₂ and crude oil, while the production well pressure is lower than the minimum miscibility pressure of CO₂ and crude oil. CO₂ cannot be miscible with crude oil near the bottom of the production well, so CO₂ cannot give full play to its stimulation effect. However, the total pressure difference between injection well and production well in well pattern element is much larger than that under experimental conditions. So the elastic expansion effect of subsequent N₂ could be fully played. Under the combined action of the two factors, the CO₂ pre-slug optimal size of CO₂-N₂ compound flooding in the five-point well pattern unit is 0.1 PV bigger than that in the laboratory core flooding experiment.

5 Conclusions

(1) The dynamic distribution of hydrocarbon phase during displacement in long slim-tube model shows that too small CO₂ slug size cannot prevent the impact of N₂ channeling on the miscible flooding, and the CO₂ slug size should have at least 0.3 PV to effectively prevent the impact of N₂ channeling.

(2) The flooding experimental results of low permeability and ultra-low permeability natural core show that with CO₂ pre-slug size increasing, the recovery of CO₂-N₂ compound flooding increases continuously. When the CO₂ pre-slug size is 0.3 PV, a better effect can be achieved. Moreover, compared with the low permeability core, the ultra-low permeability core can obtain a better flooding effect by adopting CO₂-N₂ compound flooding.

(3) In the five-point well pattern of low permeability and ultra-low permeability reservoirs, CO₂-N₂ compound flooding can achieve similar flooding effect with full CO₂ flooding. Comprehensive analysis of oil recovery and the gas cost of per ton oil showed that 0.4 PV CO₂ pre-slug size is optimal for CO₂-N₂ compound flooding.

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References

1. P. Guo, Y. Huang, X.L. Li. Influence of permeability and pressure on CO₂ displacement efficiency in low permeability reservoir. *Fault-block Oil & Gas Field*, 20(6), 768-771(2013)
2. M.T. Li, W.W. Shan, X.G. Liu, et al. Laboratory study on miscible oil displacement mechanism of supercritical carbon dioxide. *Acta Petrolei Sinica*, 27(3), 80-83 (2006)
3. T.J. Yang, Y.Z. Zhang, Z.M. Yang, et al. Mechanism of enhanced oil recovery by CO₂ flooding in tight sandstone reservoirs. *Science Technology and Engineering*, 19(24), 113-118 (2019)
4. X.L. Chen, J.S. Qin, K. Zhang. Flowing characteristics of CO₂-oil system in miscible phase flooding in porous media. *Earth Science(Journal of China University of Geosciences)*, 34(5), 94-98 (2009)
5. F.L. Zhao, M. Zhang, J.R. Hou, et al. Determination of CO₂ miscible condition and near-miscible region flooding in low permeability reservoir. *Oilfield Chemistry*, 35(2), 273-277 (2018)
6. Y. Tang, X.M. Zhao, Y. Wang. Analysis of influence factor of minimum miscible pressure of CO₂. *Reservoir Evaluation and Development*, 8(4), 42-45 (2018)
7. M.K. Emera, H.K. Sarma. Use of genetic algorithm to estimate CO₂-oil minimum miscibility pressure: key parameter in design of CO₂ miscible flood. *Soc.Petro.Engrs.J.*, 46(1), 37-52 (2005)
8. X.L. Li, Z.Q. Li, P. Guo. Long core physical simulation for CO₂ miscible displacement. *Petroleum Exploration and Development*, 31(05), 102-104 (2004)
9. W.J. Tang, X.F. Deng, Y.L. Lu, et al. Oil displacement experiment of CO₂ flooding in tight reservoir. *Fault-block Oil & Gas Field*, 25(6), 749-760 (2018)
10. S. Bai. *Numerical simulation research on non-darcy flow of CO₂ flooding in Yshulin oilfield*. (Northeast University, Daqing, 2011)
11. Yang X. *Study on optimization of gas injection development of Xinggu-nine block*. (Northeast University, Daqing, 2018)
12. Y. Sun, Z.M. Du, L. Sun, et al. Mechanism research of enhancement oil recovery by CO₂ pushed by N₂. *Journal of Southwest Petroleum University (Science & Technology Edition)*, 34(3), 89-96 (2012)
13. T.P. Chen, B. Zhao, R. He. CO₂ and N₂ flooding methods in ultra-low permeability oil reservoir.

Petroleum Geology and Oilfield Development in
Daqing, 37(4), 127-132 (2018)