 https://doi.org/10.1051/e3sconf/202020602017

The optimization of pre-slug size in CO_2-N_2 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 CO_2 and N_2 in the oil and gas phase in the CO_2-N_2 compound flooding process was numerically simulated by using the long slim-tube model. The results show that the CO_2 slug should have at least 0.3 PV to prevent the impact of N_2 channeling effectively. Second, under the experimental conditions of complete miscibility of CO_2-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 CO_2-N_2 compound flooding with 0.3 PV CO_2 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 CO_2-N_2 compound flooding and full CO_2 flooding at 300 m well spacing of low and ultra-low permeability layer. According to the simulation results, the optimal CO_2 pre-slug size in CO_2-N_2 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, CO_2 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 CO_2 flooding. Basic theories such as factors affecting CO_2 flooding efficiency[1], miscible flooding mechanism[2,3], flow in a porous medium characteristics of CO_2 flooding[4], and determination of near-miscible flooding region[5] have been explored. The factors affecting the minimum miscibility pressure of CO_2-crude oil[6] and the determination method of the minimum miscibility pressure[7] were studied. The long core physical model experiment of CO_2 miscible flooding[8], the CO_2 flooding experiment of ultra-low permeability-tight reservoir and so on[9] were carried out in laboratory. By using reservoir numerical simulation technology, the CO_2 flooding simulation calculation under non-darcy flow condition[10] was carried out, etc., and the CO_2 miscible flooding scheme and development mode were optimized[11].These studies provide a theoretical basis for CO_2 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 CO_2 and N_2 effects miscible phase between CO_2 and crude oil, the CO_2 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 CO_2-N_2 compound flooding in low permeability and ultra-low permeability reservoir are carried out. The size of CO_2 pre-slug in CO_2-N_2 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.

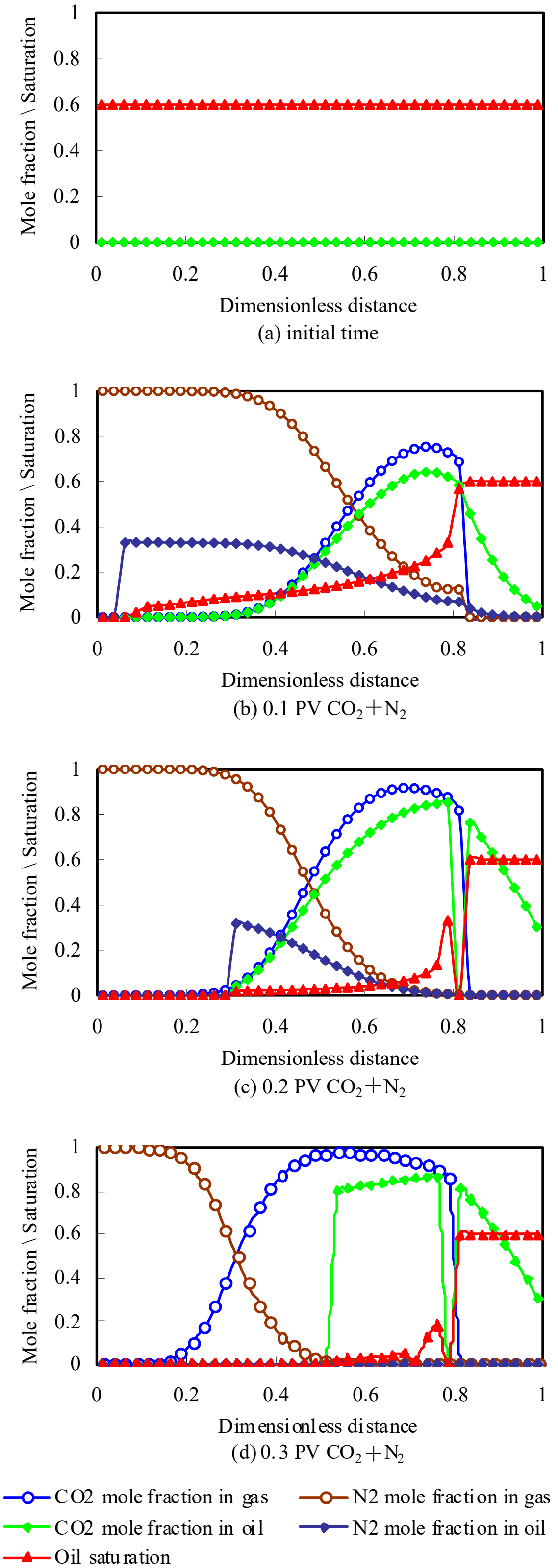

Fig. 1. Dynamic distribution of CO_2 and N_2 in hydrocarbon phase by CO_2-N_2 compound flooding

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 17.91×10-3 μm2 and 21.49%. The average effective permeability and average porosity of ultra-low permeability core are 2.26×10-3μm2 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

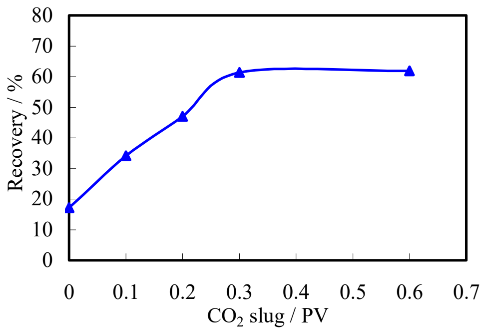

Fig. 2. Relation curve between low permeability core recovery and CO_2 slug size

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.

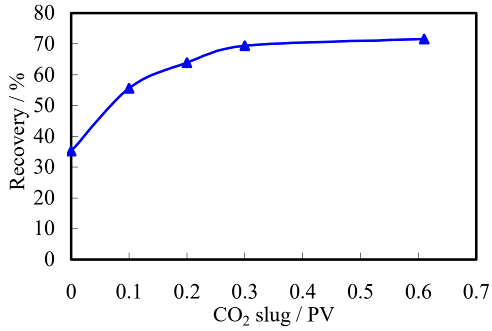

Fig. 3. Relation curve between ultra-low permeability core recovery and CO_2 slug size

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 silm-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 30×10-3μm2 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 silm-tube model. The size of the model is 212 m long × 212 m wide × 10 m high and its grid division is 106×106×5.

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.

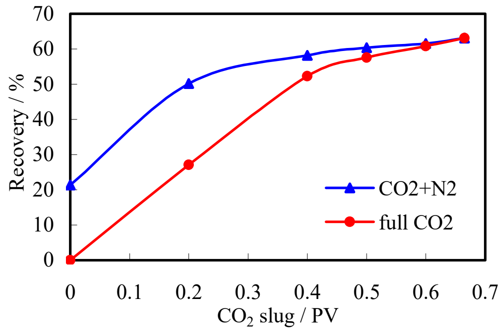

Fig. 4. Relation curve between low permeability reservoir recovery and CO_2 slug size

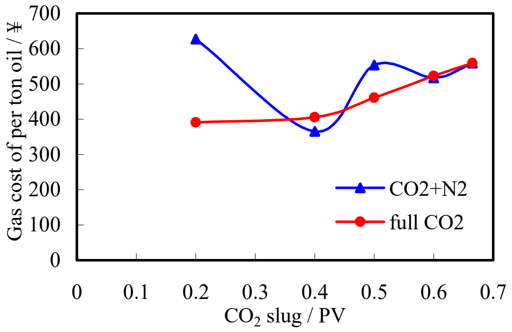

Fig. 5. Relation curve between the low permeability reservoir gas cost of per ton oil and CO_2 slug size

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 3×10-3μm2 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.

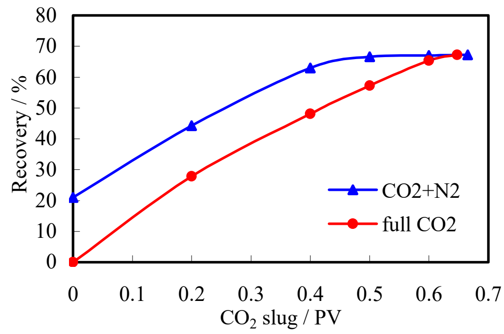

Fig. 6. Relation curve between ultra-low permeability reservoir recovery and CO_2 slug size

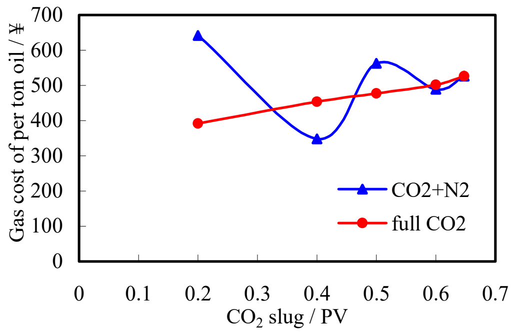

Fig. 7. Relation curve between the ultra-low permeability reservoir gas cost of per ton oil and CO_2 slug size

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.

Acknowledgements

Thanks to the Heilongjiang provincial science Foundation project “Basic research on the mechanism of CO2 geological burial and CO2 Injection in gas Reservoirs to enhance the recovery (LH2020E096)”.

Thanks to the 13th Five-Year national science and technology major projects “The new technology of high efficiency EOR in low permeability-compact reservoir (2017ZX05009-004)”.

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