Evaluation of Development Effect for CO_2 Flooding After Water Flooding in Low Permeability Reservoirs-A Case Study of a Well Group in Hei46 Block, Jilin Oilfield

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Abstract. China is rich in low-permeability oil resources. But due to the complex pore structure and strongly heterogeneity in reservoirs, it is difficult to form an effective replacement system, and the recovery of water flooding is low. CO_2 flooding is a new green idea to increase production by combining the advantages of improving the recovery of low-permeability reservoirs and achieving greenhouse gas emission reduction. At present, most of the research is focused on experimental effect evaluation and theoretical analysis, and it is difficult to form practical experience to effectively guide oilfield development. Therefore, the development effect of long-cycle WAG injection and short-cycle WAG injection after water flooding was analyzed by dynamic analysis, taking a well group in Hei46 block, Jilin Oilfield, as an example. The study results showed that the formation pressure decreases in the late stage of water-driven development, and the continuous injection of CO_2 for a long period of time to recover the formation energy also directly leads to serious gas channeling. The oil decreases and water cut rises more quickly with worse development effect instead. Continuous gas injection followed by continuous water injection to inhibit gas breakthrough can only partially restore productivity. Compared to long-period WAG injection, short-period

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WAG is the most important way to achieve oil productivity, control gas breakthrough and improve development effect. Based on the above research results, four measures are proposed to promote the development effect. The results of the study can provide an empirical reference for the development of CO_2 flooding in the late stage of water flooding for similar low permeability reservoir in China.

Keywords: Low permeability reservoirs · CO_2 flooding · gas channeling · WAG injection · dynamic analysis

1 Introduction

Low permeability reservoirs in China, generally defined as reservoirs with reservoir air permeability less than 50×10^{-3} μm^2 [1]. In China, low-permeability petroleum resources are abundant, with prospective resources of about 537×10^8 t. They are widely distributed and mainly located in the Songliao, Ordos, and Bohai Bay basins [2]. However, due to the complex pore structure and severe heterogeneity, it is difficult to establish an effective replacement system for low-permeability reservoirs, and the recovery enhancement by conventional water drive is low, so there is an urgent need to explore effective technologies to enhance oil recovery. CO_2 injection is one of the important CCUS technologies, and it is a new green idea for enhancing oil production because of the significant effect of reducing interfacial tension, swelling and viscosity reduction after gas injection and easier to form an effective replacement system [3], which has the advantages of both improving the recovery of low-permeability reservoirs and achieving greenhouse gas emission reduction.

In recent years, many scholars have conducted experimental studies related to CO_2 driving for enhanced oil recovery. Zhang, H. L. [4] clarified that the CO_2 miscible flooding can displace the crude oil in the low-porosity and low-permeability reservoirs which cannot be flooded by the water. Zhou, X. et al. demonstrated that the effect of different gas injection methods and operating parameters on the development effect through long core replacement experiments [5]. Li, Y. et al. showed that the oil drive efficiency tends to increase with increasing pressure through CO_2 flooding experiments in long cores, but there are differences in the shape of the flooding efficiency curve [6]. Zhang, B. Y. et al. confirmed that the recovery could be improved by 3.14% based on natural depletion through multi-cycle CO_2 huff-puff experiments [7]. Wang, Y. F. et al. studied the heterogeneity on enlarging sweep volume through core replacement experiment and NMR technique. The WAG injection of CO_2 performs well in EOR after water flooding for all the cores with different heterogeneities; however, it could barely form a complete or full sweep throughout the low-permeability region, and un-swept bypassed regions remain [8]. In addition to experimental studies, many scholars have used numerical simulations to demonstrate the effect of different parameters on CO_2 flooding. Ding, S. W. et al. used numerical simulation to demonstrate the adaptability of three different injection methods, Continuous gas injection (CGI), Constant water alternating gas (CWAG), and Tapered water alternating gas (TWAG), for enhanced recovery and geological storage [9]. Kashkooli, S. B. et al. used a commercial reservoir simulator to prove that the main benefit of optimization of CO_2 sequestration and CO_2 flooding appeared after the CO_2 breakthrough in an under-unsaturated oil reservoir with CO_2 flooding [10].

From the above literature, it is easy to find that many scholars have demonstrated the advancement and feasibility of CO_2 flooding to enhance oil recovery through experiments or numerical simulations, but it is still difficult to utilize directly to guide the practical development of the field. Therefore, this paper takes a well group in Hei 46 block of Jilin Oilfield as an example to discuss in detail the effect of CO_2 injection in the late stage of water-driven development, in the hope of providing an empirical reference for CO_2 flooding in the late stage of water-driven development of the same type of low-permeability reservoirs in China.

2 Block Overview

CO_2 capture, flooding and storage (CCUS-EOR) project of Jilin oil field has gone through five stages: indoor experiment, trial injection test, pilot test, expanded test and industrial application, and has built the first full industry chain and whole process demonstration project of CCUS-EOR in China, which is the only Chinese project among the 21 large CCUS projects in operation worldwide, with a cumulative oil of 32×10^4t and cumulative CO_2 storage of 250×10^4t [11, 12]. The Hei46 block is one of the 5 types of CCUS demonstration areas in Jilin oilfield.

2.1 Geological Overview

The overall structural form of Hei46 block is a northwest-trending monoclinic structure with a gentle dip of about 1.5°. In the west is a reverse positive fault of northeast-east tendency, and there are several fault-nose traps in the block. The sedimentary characteristics are the deltaic foreland sedimentary environment. The main development layer system includes 7, 12 and 14 in member 1 of the Qingshankou Formation and 4 and 5 in member 4 of the Quantou Formation. The physical properties of the reservoir are poor. The average porosity of each main layer is 14.4% and the average permeability is 6.32 mD with the average sand body thickness of 4.38 m, which is a low-porosity and low-permeability reservoir.

2.2 Production Overview

The well group consists of eight wells, with one injection well (Inj-1) in the middle and seven production wells (Pro-1 to Pro-7) distributed around it, which belongs to a diamond-shaped inverse nine-point well pattern (see Fig. 1). The well group developed by water injection from 2003 to 2014, with an average daily water injection of 30 tons. The average daily liquid production was maintained at 30–45 tons/day and the average daily oil production dropped from 30 tons/day to 7 tons/day during the stage. The watercut continued to rise from 40% to 70%. In 2014, the well group started injecting CO_2 to enhance oil recovery. After CO_2 injection, the overall liquid production decreased to an average of 20 tons/day and the oil production stopped the decreasing trend as well as maintaining at 7 tons/day. The watercut slowly increased to 75%. After starting CO_2

injection, the CO_2 percentage in the production well gradually increased to a maximum value of about 65%. The gas-oil ratio starts with a small change and rises sharply to a peak of 1037 m^3/ton at the later stage. When the short-cycle WAG is implemented, the CO_2 percentage and gas-oil ratio gradually decrease (see Fig. 2). Up to now, CO_2 injection has been developed for about 8 years, but the development effect of CO_2 injection is not obvious, so a systematic dynamic analysis of this well group was conducted.

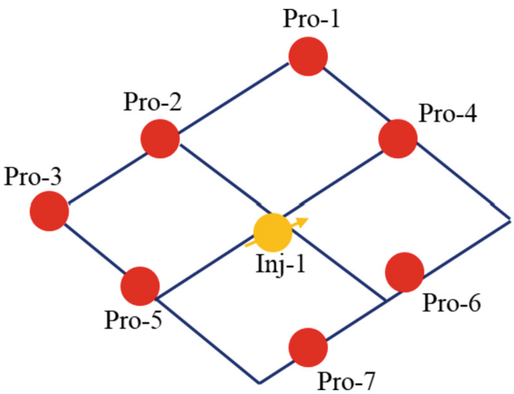


Fig. 1. A diamond-shaped inverse nine-point well pattern in the well group

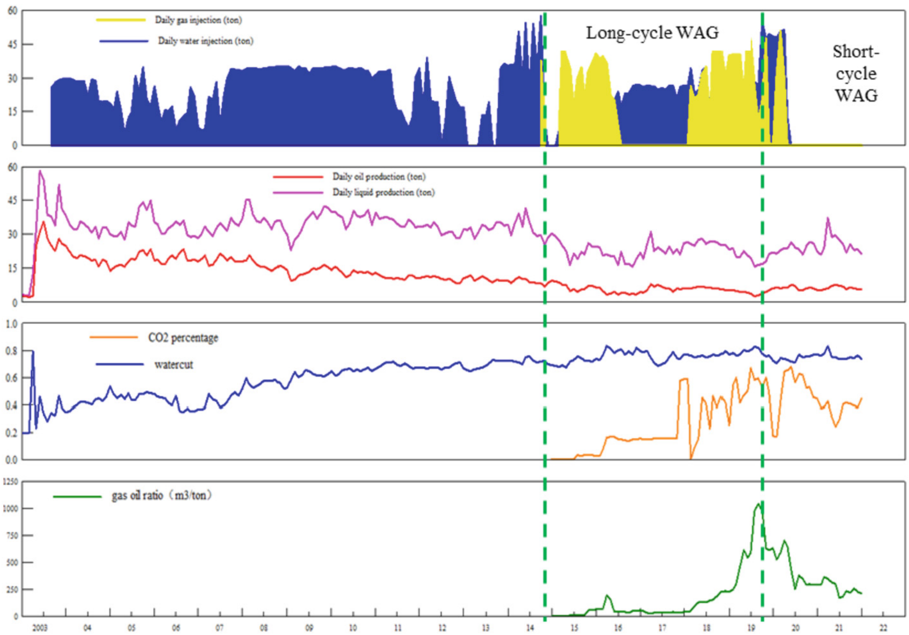


Fig. 2. Dynamic analysis curve of the well group

3 Dynamic Analysis

3.1 Stage Division

According to the gas and water injection of Inj-1, the stage of this well group is divided into 2 major categories after CO_2 injection, from January 2014 to September 2019 for the long-cycle WAG, and from September 2019 to present for the short-cycle WAG. The long-period WAG phase can be further subdivided into continuous gas injection phase (First), continuous water injection phase and continuous gas injection phase (Second) (see Fig. 3). The production curve from well Pro-1 to well Pro-7 is shown in Fig. 4.

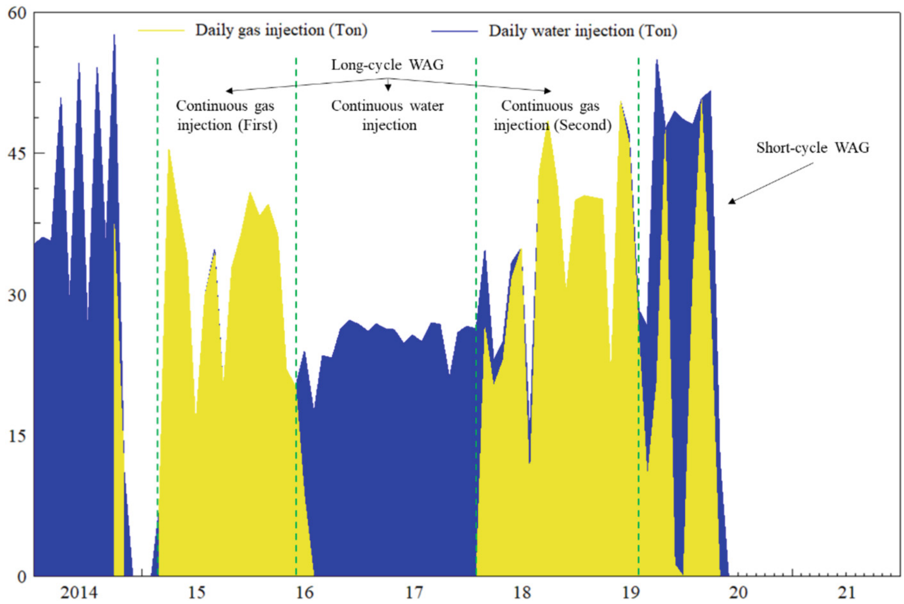
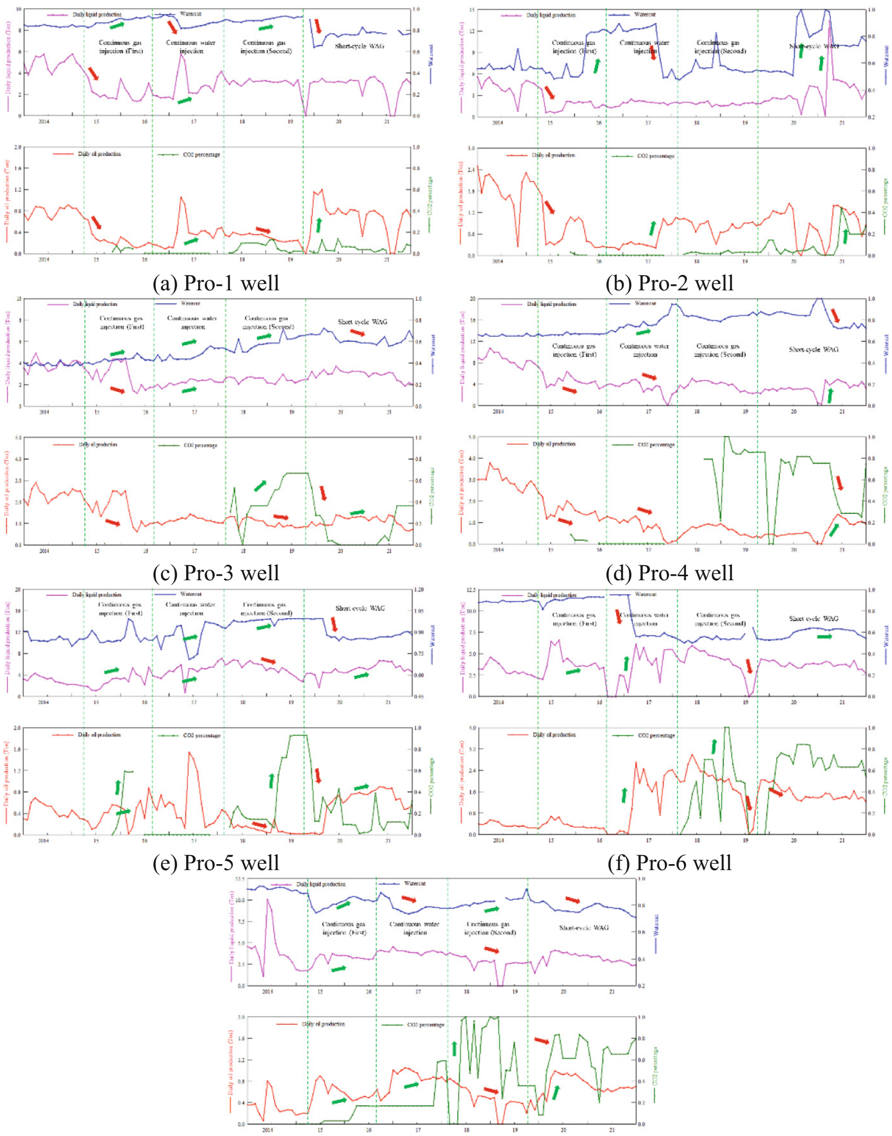


Fig. 3. Analysis of WAG phase in detail

3.2 Long-Cycle WAG

Continuous Gas Injection (First)

During the first continuous gas injection phase, liquid production from the Pro-1 well decreased from an average of 5 tons/day to 2 tons/day, oil production decreased from an average of 0.8 tons/day to 0.25 tons/day, while watercut slowly increased from 80% to 90%. The CO_2 percentage remained at a low level, indicating that CO_2 had not yet caused gas channeling at this time. Pro-2 well liquid production decreased slowly, with a sharp increase in watercut in the late stage. The oil production decreased with fluctuations. The CO_2 percentage maintained at a low level, indicating that CO_2 had not yet caused gas channeling at this time. Liquid production from the Pro-3 well slowly decreased from an average of 4 tons/day to 2 tons/day, and oil production slowly decreased from



(a) Pro-1 well
(b) Pro-2 well
(c) Pro-3 well
(d) Pro-4 well
(e) Pro-5 well
(f) Pro-6 well
(g) Pro-7 well

Fig. 4. The production curve from well Pro-1 to well Pro-7

an average of 2 tons/day to 1 ton/day. The watercut increased from 40% to 45% slowly. The liquid production of Pro-4 well decreased from an average of 8 tons/day to 4 tons/day and oil production decreased from an average of 2.5 tons/day to 1.5 tons/day, and the watercut remained stable at around 65%. The CO_2 percentage maintained at a low level, indicating that CO_2 had not yet caused gas channeling at this time. Pro-5 well recovered slowly from 2 to 4 tons of liquid per day. Oil production slowly recovered from 0.4

tons/d to 0.6 tons/d. But the change process is fluctuating. The watercut fluctuated at 90%. CO_2 percentage increased rapidly from 0 to 60%. Liquid production from the Pro-6 well slowly increased from 2.5 tons/day to 3.5 tons/day, and oil production and watercut remained stable. The liquid production of Pro-7 well increased slowly from 2 tons/day to 3.5 tons/day, and oil production increased slowly from 0.2 tons/day to 0.6 tons/day. The watercut decreased first and then increased. The CO_2 percentage increased slowly. The results of all analyses can be seen in Table 1.

Table 1. The development effect of Continuous gas injection (First)

Well	Liquid production	Oil production	Watercut	CO_2 percentage	Development effect
Pro-1	Decrease	Decrease	Increase	At a low level	Poor
Pro-2	Decrease	Decrease	Increase	At a low level	Poor
Pro-3	Decrease	Decrease	Increase	No measurement	Poor
Pro-4	Decrease	Decrease	No change	At a low level	Poor
Pro-5	Increase	Increase	Fluctuation	Increase	Good
Pro-6	Increase	No change	No change	No measurement	General
Pro-7	Increase	Increase	Increase	At a low level	Good

Continuous Water Injection

During the continuous water injection phase, the liquid production of the Pro-1 well increased from 2 to 4 tons/day. The oil production increased from 0.25 to 0.4 tons/day. The watercut decreased and then increased, and the watercut at the end of the phase decreased slightly compared to that at the beginning of the phase. At the end of the phase, the oil production of pro-2 well increased sharply to 1 tons/days and the watercut decreased sharply to 50%. Liquid production remains stable compared to previous. Liquid production from the Pro-3 well increased slowly, with oil production rising and then falling and watercut continuing to rise from 45% to 55%. The Pro-4 well's liquid production dropped from 4 tons/day to 2.5 tons/day, oil production dropped from 1.2 tons/day to 0.2 tons/day, and the watercut rose sharply to nearly 96%, putting the well at risk of shut in. The liquid production of the Pro-5 well slowly increased from 4 to 6 tons/day, with repeated fluctuations in oil production and a slow increase in water content to 95%. The liquid production of Pro-6 well increased to 5 tons/day, and oil production increased to 2.4 tons/day. The watercut decreased from 95% to about 60%. Liquid production from the Pro-7 well remained stable, with oil production rising to an average of 0.8 tons per day and watercut slowly decreasing to 80%. CO_2 percentage rose to 60% towards the end of the stage. The results of all analyses can be seen in Table 2.

Continuous Gas Injection (Second)

During the second continuous gas injection phase, the fluid production of the Pro-1 well remained stable, oil production slowly decreased and watercut slowly increased to 93%. Small increase in CO_2 percentage. The well was forced to shut in at the end of this period. The Pro-2 well produced stable liquid and oil compared to previous. The

Table 2. The development effect of Continuous water injection

Well	Liquid production	Oil production	Watercut	CO_2 percentage	Development effect
Pro-1	Increase	Increase	Decrease	No CO_2	Good
Pro-2	No change	Increase	Decrease	No CO_2	Good
Pro-3	Increase	No change	Increase	No measurement	General
Pro-4	Decrease	Decrease	Increase	No CO_2	Very poor
Pro-5	Increase	Fluctuation	Increase	No CO_2	General
Pro-6	Increase	Increase	Decrease	No measurement	Very good
Pro-7	No change	Increase	Decrease	Increase	good

watercut increased slowly. The liquid production of the Pro-3 well remained stable, and the oil production dropped from 1.2 tons/day to 0.9 tons/day, and the watercut increased sharply from 50% to 65%. The CO_2 percentage increased sharply to more than 60%, indicating that the CO_2 has undergone gas channeling. The liquid production and oil production of the Pro-4 well first increased and then decreased, and the watercut first decreased and then increased. The CO_2 percentage has exceeded 80%, which indicated that the gas channeling was serious at this time. Liquid production from Pro-5 well declined slowly from 6 tons/day to 3.5 tons/day, with oil production dropping to almost zero and watercut approaching 100%. The CO_2 percentage approached 90% at the end of the stage and the well was at serious risk of shut in. The liquid production and oil production of the Pro-6 well dropped sharply at the end of this stage, and the watercut remained stable. The CO_2 percentage increased sharply, and CO_2 gas channeling was serious. The liquid production of Pro-7 well decreases slowly to 2.5 tons/day, and the oil production decreases rapidly from 0.8 tons/day to 0.4 tons/day and the watercut increases slowly. The CO_2 percentage fluctuates around 100%, which indicates serious gas channeling. The results of all analyses can be seen in Table 3.

Table 3. The development effect of Continuous gas injection (Second)

Well	Liquid production	Oil production	Watercut	CO_2 percentage	Development effect
Pro-1	No change	Decrease	Increase	Small increase	Poor
Pro-2	No change	No change	Increase	Small increase	General
Pro-3	No change	Decrease	Increase	Gas channeling	Very poor
Pro-4	No change	Increase	Decrease	Gas channeling	General
Pro-5	Decrease	Decrease	Increase	Gas channeling	Very poor
Pro-6	Decrease	Decrease	No change	Gas channeling	Very poor
Pro-7	Decrease	Decrease	Increase	Gas channeling	Very poor

3.3 Short-Cycle WAG

In this stage, the liquid production of the Pro-1 well remained stable compared continuous gas injection (Second) and oil production rose sharply, recovering from shut-in to 0.8 tons/day with a 15% decrease in watercut. The CO_2 percentage remained at a low level. The effect of short-period WAG is beginning to show. Pro-2 well liquid production rose rapidly in the late stage, with large fluctuations in oil production and a sharp increase in watercut. The CO_2 percentage increased sharply to 40% at the end of this phase. The liquid production of the Pro-3 well remained stable, and the oil production increased slightly. The watercut stopped the rising trend and remained stable at 60%. The CO_2 percentage dropped sharply, and the gas channeling was effectively mitigated. The Pro-4 well showed a small increase in liquid production and oil production towards the end of the stage, and a 10% decrease in watercut and a significant decrease in CO_2 percentage. The effect of water reduction and oil enhancement is remarkable. The Pro-5 well produced more liquid slightly, up 6 tons/day from 3.5 tons/day, and oil production recovered to 0.8 tons/day from near shut-in status, with a 10% decrease in watetcut and a significant reduction in CO_2 percentage. It is effective in suppressing gas channeling while significantly reducing water and increasing oil. Liquid production from the Pro-6 well recovered to the average level in continuous gas injection (Second) with a slight decrease in oil production and a small increase in watercut. The CO_2 percentage maintained between 60% and 80%. The liquid production of Pro-7 well increased firstly and then decreased slowly. The oil production increased sharply and then decreased slowly. The watercut decreased slowly to 70% and the CO_2 percentage dropped slightly, and the effect of enhancing oil recovery gradually appeared. The results of all analyses can be seen in Table 4.

Table 4. The development effect of Short-cycle WAG

Well	Liquid production	Oil production	Watercut	CO_2 percentage	Development effect
Pro-1	No change	Increase	Decrease	At a low level	Very good
Pro-2	Increase	Fluctuation	Increase	Increase	Poor
Pro-3	No change	Increase	Decrease	Decrease	Good
Pro-4	Increase	Increase	Decrease	Decrease	Good
Pro-5	Increase	Increase	Decrease	Decrease	Very good
Pro-6	Increase	Decrease	Increase	No change	General
Pro-7	Increase	Increase	Decrease	Decrease	Good

3.4 Comprehensive Analysis

From parts 3.2 and 3.3, it can be seen that under the effect of long-cycle WAG, the effect of oil increase and water reduction is not significant, especially in the second continuous gas injection stage with gas channeling for most of the wells in this group. Looking at each subdivision stage, at the first continuous gas injection, four of the seven wells were instead poorly produced, two wells were well produced, and one well had insignificant changes. During the continuous water injection phase, some wells were able to return to productivity. During the second continuous gas injection phase, the development effect of all wells was poor, most of them even experienced severe gas channeling, and many of them were at risk of shut in. During the short-cycle WAG phase, all wells showed significantly results of improving recovery compared to the previous ones, with increased oil production and lower watercut. The beginning of lower CO_2 percentage, which improved oil recovery while avoiding severe gas channeling.

4 Suggestions

Based on the above analysis, the following measures are preferred to improve the development effect of the block: (1) strengthen the intensity of WAG and shorten the interval of WAG. Besides, increasing the water injection to inhibit gas channeling as well as expanding the swept volume. (2) The wells of gas channeling are adjusted, and the production wells are changed into injection wells, and the injection wells are changed into production wells. (3) For unused zones, re-perforation fracturing is performed. (4) To restore the production of wells that have been shut down for a long time and promote the uniform flooding effect (see Fig. 5).

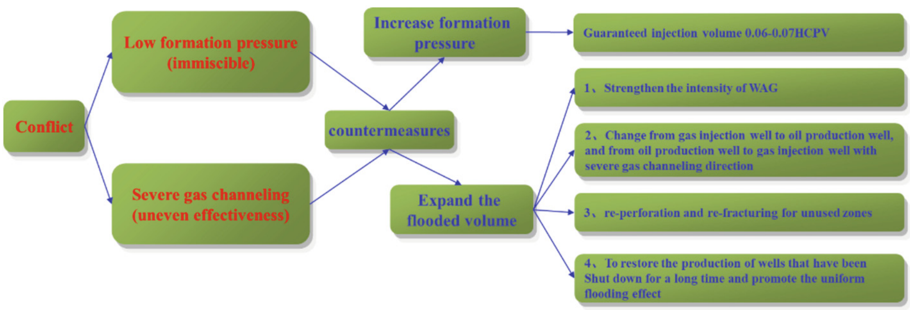


Fig. 5. Flow chart to improve the effect of development

Well group A is another typical well group in Hei46 Block, with initial continuous gas injection of 20–30 tons/day. The oil production rate is 4–5 tons/day, and the gas production rate is about 10000m3/d with water cut of nearly 85%. The development effect is not significant. After re-perforation and re-fracturing, the oil production gradually increased to 7.5 tons/day, and the water content decreased to 75%. Besides, by improving injection intensity and optimizing the slug of WAG, the relationship between producer and injector is improved and the vertical effectiveness difference by different countermeasures is reduced. The oil production has increased to 11 tons/day, the water content has decreased to 70–75%, and the gas production has further decreased to 4000m3d. From the suction profile, the overall suction profile in 2019 is more uniform than in 2016, avoiding the rapid migration of CO_2 along the high permeability channel, leading to severe gas channeling (see Fig. 6 and Fig. 7).

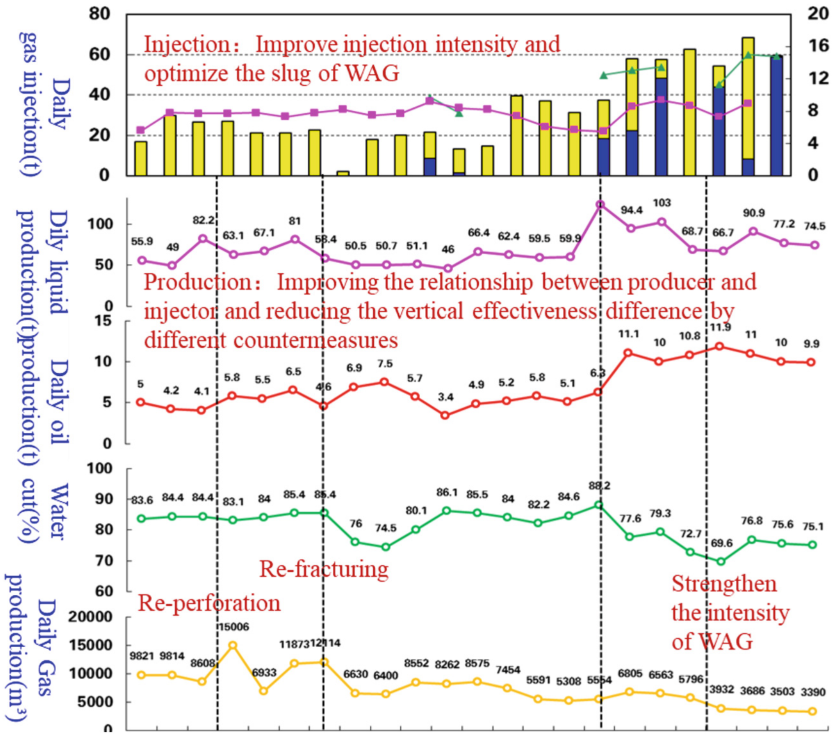


Fig. 6. Dynamic analysis of typical well group

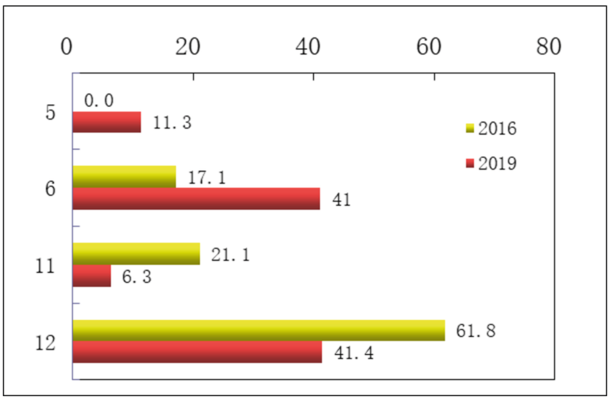


Fig. 7. Suction profile in 2016 and 2019

5 Conclusions

The study results showed that the formation pressure decreases in the late stage of water-driven development, and the continuous injection of CO_2 for a long period of time to recover the formation energy also directly leads to serious gas channeling. The oil decreases and water cut rises more quickly with worse development effect instead. Continuous gas injection followed by continuous water injection to inhibit gas breakthrough can only partially restore productivity. Compared to long-period WAG injection, short-period WAG is the most important way to achieve oil productivity, control gas breakthrough and improve development effect. Based on the above research results, four measures are proposed to promote the development effect. The results of the study can provide an empirical reference for the development of CO_2 flooding in the late stage of water flooding for similar low permeability reservoir in China.

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