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Effectiveness of In-Situ Microbial Enhanced Oil Recovery in a Post-Polymer Flooded Reservoir

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Abstract
This study investigated the effectiveness of In-situ microbial enhanced oil recovery (IMEOR) in a post-polymer flooded oil reservoir located in SaNan oilfield, Northeast China. Two rounds of injection of nutrient medium were intermittently injected into the producing block and then monitored. The main results showed that the dominant bacteria of 4 production wells, Thauera of Beta-proteobacteria, Pseudomonas and Acinetobacter of Gamma-proteobacteria were directional activation, which showed a consistent enhancement. The abundance of Methanosaeta and Methanolinea increased, and showed a regular alternation with an increase of oil production. It contributed to production of bio-gas, leading to increasing of the injection pressure from 11.3 MPa to 13.9 MPa before the experiment which increased by more than 2.0 MPa. The contents of CO_2 and CH_4 varied alternately, and the variation was consistent with the order of injection of each activator. H_2 was detected in the reservoir associated with the gas in the observation area. A large amount of enriched bio-gas was dissolved into and mixed with crude oil, which brought increasing of the proportion of light components in the whole hydrocarbon of the recovered oil. The other effect was activated microbial metabolites productions formed bio-plugs, which benefits for improving of the absorption profile and the production profile. A total of 6,243 t of incremental oil production was achieved, and an oil recovery rate increased by 3.93% (OOIP) to the end of 2015. Our trial suggested that IMEOR can be implemented for effective enhancement of further oil recovery from polymer flooded oil reservoirs.

Keywords: Post-polymer flooded Reservoir, Activator, In-situ microbial, Bio-gas, Bio-plug, In-situ microbial enhanced oil recovery (IMEOR).

Introduction
Daqing Oilfield is the first one in China for large scale production since 1960. The OOIP is 1.118 billion tons and 56.5% of the OOIP has been produced. The tested fields with 83 industrialized blocks have been produced by water and polymer flooding in sequence by the end of 2016. How to effectively recover the residual oil in post-polymer flooded high water-cut reservoirs is of strategic importance for oil industry. In-situ microbial enhanced oil recovery (IMEOR) may be a promising alternative oil-recovery technique for these reservoirs. Compared with polymer flooding, IMEOR is of low energy consumption, low environmental impact, and cost effective. In recent years, this technology has been intensively developed, and has breakthroughs in oil displacement mechanisms, analysis of microbial structure, activator optimization and field application [1-11].

IMEOR is to stimulate growth of microbes by injecting nutrient solutions into subterranean formations of oil reservoirs. The effects of microbes and microbial metabolites productions which have characteristics such as increasing displace energy by a gas-producing microbes generate a sufficient amount of bio-gas, and form bio-plugs to improve sweep efficiency etc. This technique has a complex biochemical processes to extract the remaining oil from reservoirs.

In this study, an improved IMEOR process was designed and tested in a post-polymer flooded high water-cut reservoir in Daqing Oilfield from 2012 to 2013 [11]. The microbial dynamic characteristics of the stimulated community after polymer flooding were studied. The relationships between oil production performances and IMEOR process were analyzed. The mechanism of activated microbial flooding was further investigated using advanced molecular technique. The results provided first-hand information for further expansion of this practice to their reservoirs of similar characteristics [2].

Materials and Methods
Reservoir description
The test area located in the eastern part of SaNan block, Daqing, Heilongjiang, China. It was composed of 1 injection well (N2-2-P40) and 4 production wells (N2-D2-P40, N2-2-P140, N2-2-P141, N2-D3-P40) in a relatively closed area (0.12 km^2) (Fig. 1).

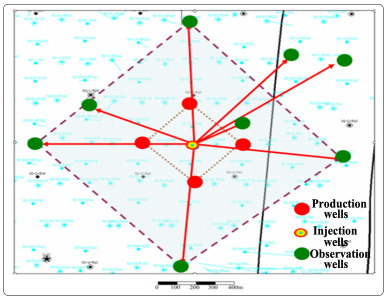

Figure 1: Test wells and observation wells

The distance between the injection wells and the production wells was about 250 m. The recovered oil-bearing strata was P I1-4, with an average thickness of 14.3 m of sandstone at a single well, the effective thickness of 9.2 m, the geological reserves of 15.9×10^4 t, the pore volume of 27.26×10^4 m^3, the average effective permeability of 414×10^{-3} μm^2, the reservoir temperature of 44.6 ºC, the initial formation pressure of 11.66 MPa, and the saturation pressure of 7.5 MPa.

The degree of mineralization of the injection water and the formation production fluid in the test area was 6,130 mg/L and 4,540 mg/L, and the pH value was 8.35 and 8.30, respectively. The wax content of crude oil was 30.7%, with the crude oil density of 0.8491 g/cm^3 and the viscosity of 21.0 mPa•S, the original oil and gas ratio of 45.3 m3/t, the volume coefficient of 1.118; the natural gas relative gravity was 0.6606, with the CH_4 content of 85.6%, the CO_2 content of 0.78%. Before the experiment, the block had been water-flooded for 6 and half years, with the comprehensive water cut of 96.1%, and the recovery degree of 61.89%. The remaining oil was mainly concentrated in the P I_3 and the P I_4 reservoirs, which was in the typical "double high" (high water cut and high recovery degree) stage.

The implementation process

According to physical simulations of oil displacement in laboratory screening tests, activator was selected with a concentration of 1.34% [2, 11]. The first round of injection was from August 5, 2011 to April 30, 2012 with a co-injection of activator solution of 5,588 m^3 and an injection rate of 80-130 m3/d/well. Considering the existence of large pore paths of the post-polymer flooded reservoir, a small amount of hydrolyzed polyacrylamide (2,418 m^3 with a concentration of 2,000 mg/L) was initially injected into the block. The activator was separated with water to ensure concentration of activator without any significant loss in the oil layer. The cumulative amount of injection was 8,006 m^3, and the slug size was 0.0293 PV.

The second round of injection time was from December 23, 2012 to April 26, 2013 in the co-injection of activator solution of 10,023 m^3, the activator concentration of 1.34%, the injection rate of 80-130 m^3/d/well, and a concentration of 2,000 mg/L hydrolyzed polyacrylamide at 3,390 m^3, injected continuously. The cumulative quantities of injection were 13,413 m^3, and the slug size was 0.0492 PV. The total amount of activator was 15,611 m^3, with the total amount of protective agent 5,808 m^3. The total amount of liquid was 21,419 m^3 and the total slug was 0.0785 PV.

Data accessibility

The raw reads were deposited in the Gen Bank at the National Center for Biotechnology Information (BioProject ID: PRJNA349240, https://submit.ncbi.nlm.nih.gov/subs/bioproject/SUB2027000/overview).

Results and discussion

The change of microbial communities after activators injection

16S rRNA gene sequencing was performed to investigate the microbial community dynamics during the activators injection [2, 11]. The results indicated that the microbial populations of the four production wells were changed greatly. After nutrient injection, Gamma-proteobacteria obviously increased while Epsilon-proteobacteria obviously decreased in each one of the production wells. After water-flooding, Gamma-proteobacteria and Alpha-proteobacteria decreased obviously while Beta-proteobacteria, Epsilon-proteobacteria, and Delta-proteobacteria increased significantly. Moreover, there was a consistent change of the community compositions with nutrients injection. At the genus level, Thauera and Hydrogenophaga in the Beta-proteobacteria, Pseudomonas and Acinetobacter in Gamma-proteobacteria were significantly increased and became the dominant microbial flora in the four production wells when the activator was injected, showing a regular alternation with an increase of oil production (Fig. 2) [12, 13]. Both Pseudomonas and Acinetobacter are capable of producing surfactants with alkane hydrocarbons as the substrates [14, 15]. Thauera can produce bio-gas by cleavage of benzene to short-chain alkane of crude oil as an electron acceptor (C_7H_8 $+7.2NO_3$$+7.2H^+$$\rightarrow$$O_2$$+3.6N_2$$+7.6H_2O$) [16]. These bacterial populations play important roles in IMEOR [17, 18].

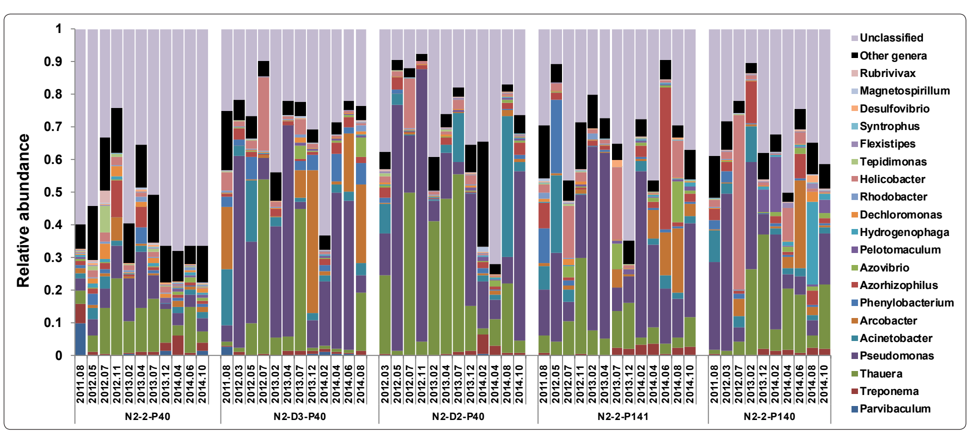

Figure 2: Dynamic changes of microbial flora and relative abundance in test area

The distribution of archaea communities in the production and injection wells was very similar before introduction of the activators. The predominant archaeal populations were Methanosaeta and Methanolinea. Methanobacterium, Methanococcus, Methanoculleus, Methanolobus, and Crenarchaeota were low abundances of. The optimal growth temperature of Methanosaeta was between 33°C and 50°C, and acetate was used as the sole substrate to produce methane. Methanolinea species use $H_2 + CO_2$ as substrates to produce methane by reductive process [19, 20]. After injection of activators, the changes of archaeal community in the injection wells were not apparent, whereas distinct changes of the relative abundance of the archaeal community in the production wells were observed. As a result, both Methanosaeta and Methanolinea increased significantly.

The bio-gas produced by the stimulated in-situ microbe

The biogenic gas includes alkane gas (C_1~C_6), non-hydrocarbon gas (CO_2 and N_2) and rare gas (H_2). The contents of CO_2 and CH_4 in each producing wells changed from non-synchronous in the first cycle to synchronous in the second cycle. H_2 was monitored at the end of the first round of activation process in the associated gas of the reservoir. In the second round, H_2 was monitored in 8 observation wells outside the pattern with 250m well spacing in the test area. The longest distance from observation well to injection well was nearly 1,000 m. This indicates that the action range of the activated microbial community and transmission region of the bio-gas in the reservoir are continuously extended to the test area.

Compared with the control, the content of CH_4 and CO_2 from the production wells increased from 83.8% to 94.7% and from 1.5% to 8.5%, respectively, at the time of nutrients injection. At the end of the injecting period for activator, the curve of CH_4 content was significantly increased near the end period (Fig. 3). The CO_2 content curve showed a downward decline, indicating that the methanogens continued to transform the metabolites into CH_4 by anaerobic fermentation at the end of the anaerobic chain [21- 23]. But, at the end of the process it was slowed down due to the decreasing availability of activator supply, and progressively returned to the original state before the experiment.

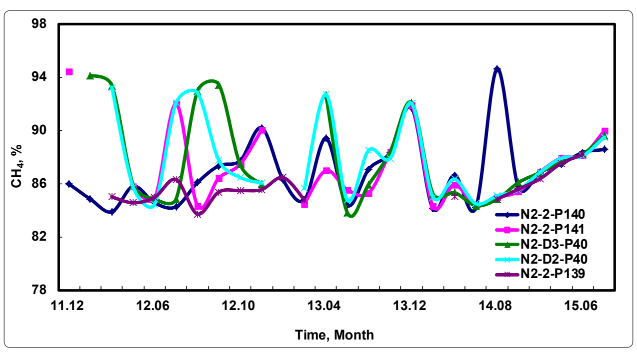

Figure 3: The dynamic change of CH_4

The $\delta^{13}C$ (Pee Dee Belemnite, PDB) of the CH_4 and CO_2 in the same monitoring range fluctuated between -54.5 ‰~-45.2 ‰ and 6.4 ‰~13.3 ‰, respectively, and the deviation from the baseline value was larger (Fig. 4). Because H_2 was not present in the original associated gas monitored in the test wells and the observation wells, the content of $\delta^{13}C$ (PDB) carbon isotope of CH_4 and CO_2 was analyzed. The CH_4 in bio-gas was partly converted from acetic acid produced through decomposition of organic matter in the activator by some different types of methanogens, while the others was converted from the reduction of $CO_2 + H_2$, which was produced from methane-degrading. The results also showed that the differences in selective degradation of activator organic matter and crude oil during the activation led to abnormal change of content of gas component and $\delta^{13}C$ (PDB) carbon isotope in each well [15].

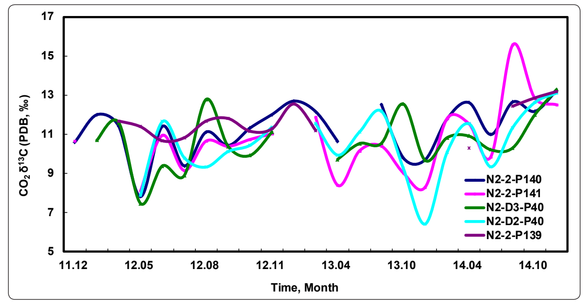

Figure 4: The content change of isotope$\delta^{13}C$ (PDB) of CO_2

The change of the injection pressure

In order to investigate the effect of gas production on incremental pressure underground during activation, the amount of injected water at a specific time was adjusted to ensure the better oil displacement effect. The strong gas production was observed after the activation in the first round, resulting in a quick increment of the wellhead injection pressure, which increased from 11.3 MPa to 12.5 MPa in the first round of activators injection. The incremental pressure was the most obvious during 15-20 days after the activator injection, and was the same as the results of the physical simulation experiments. The injection pressure of activator slug in the second round increased from 12.5 MPa to 13.5 MPa. The pressure increased 2.5 MPa cumulatively during the injection period. The pressure decreased to the initial pressure 11.0 MPa after 140 days of subsequent water flooding, and then increased to 12.5 MPa after 280 days (Fig. 5).

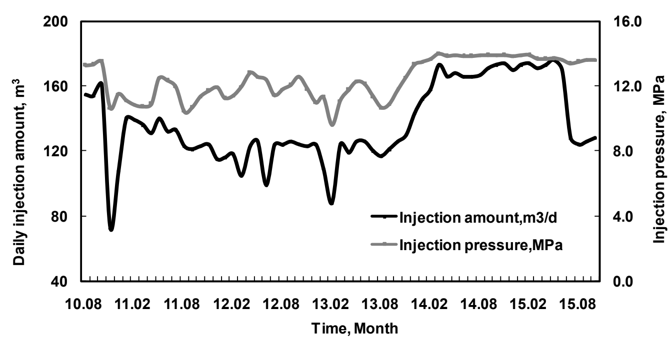

Figure 5: The change of amount and pressure of water injection before and after test

There were two stages in gas production processes. The gas pressurization rate of the first stage was high and the cycle was short, with a high content of carbon dioxide and low content of methane. The gas pressurization of the second stage was low and the anaerobic cycle was long, with a low content of carbon dioxide and high content of methane. The rise of pressure should be a long process of continuous accumulation [2,11,24].

According to the characteristics of the injection activator of the first round, the injection method and the dosage of the second round were adjusted accordingly. The amount of activator was increased, and a post-protection slug of activator was added and the water injection rate was increased, which is more conducive to improving the oil displacement. By adjusting the injection method and the injection quantity, the effect of gas production and the pressure increment of the second round were significantly improved than that of the first round. The injection pressure reached a stable level of 14MPa during nearly 15 months subsequent water flooding, which provided favorable conditions for extending the production period and improving oil production. After the end of the test, the water injection was adjusted to the base level before the test. However, the injection pressure did not decrease significantly, and remained above 13.5 MPa after four months.

The change of hydrocarbon composition of crude oil

The content of the hydrocarbon components in crude oil obtained from the first-round activation was significantly different with the second-round activation. After two rounds of activation, the residual oil in the reservoir was extracted by bio-gas dissolution effects [25, 26]. The total hydrocarbon components of crude oil were analyzed by gas chromatography, the ratio of $\Sigma nC_{21}^{-}/\Sigma nC_{22}^{+}$ in the crude oil significantly increased, the main carbon peak of alkane converted from C_{19}-C_{23} to C_8-C_{14}, and the carbon number ranged from the C_4-C_{39} to C_3-C_{38} at the later of the field trial, the structure and the content of alkanes in crude oil were changed significantly, as shown in Fig. 6 a-d [27].

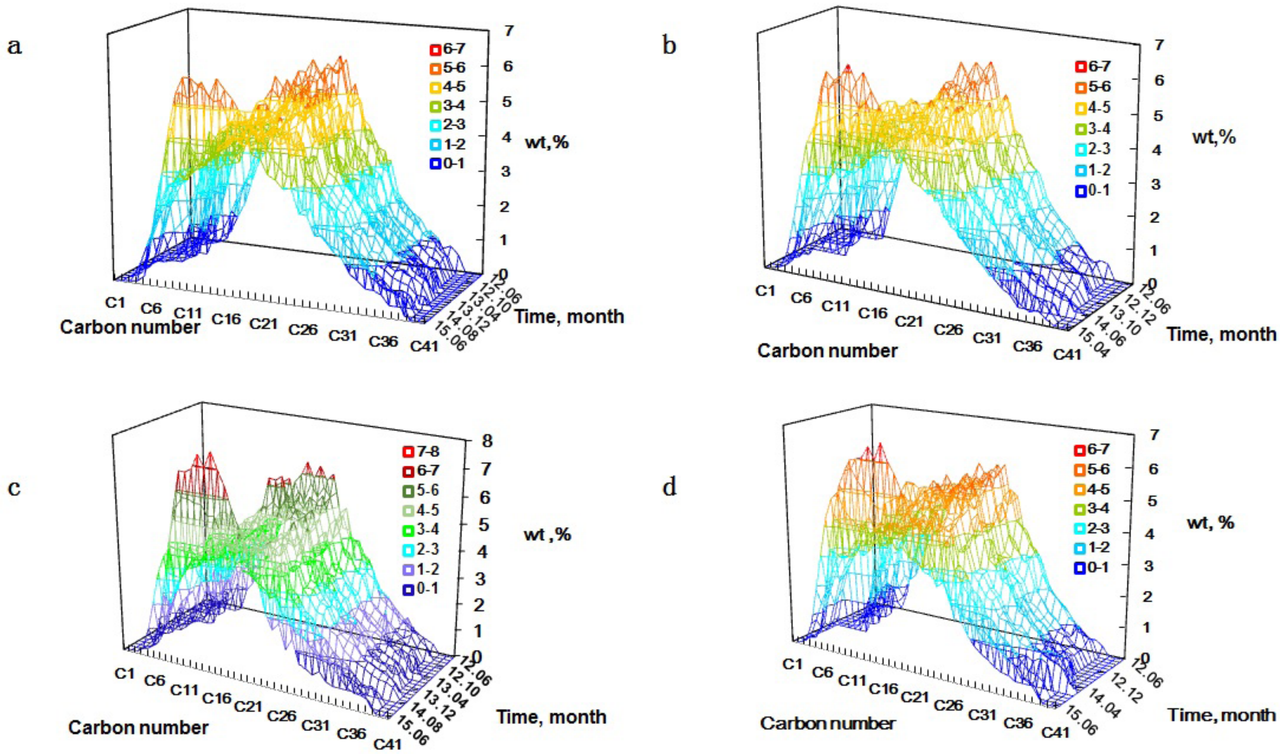

Fig.6 The content of the hydrocarbon components in crude oil before and after the activator injection. (a) N2-2-P141,(b) N2-2-P140,(c) N2-D3-P40, (d) N2-D2-P40

The reason is that the injection amount was only 0.0293PV during the first-round activator injection, which was less than 1/30 of the total pore volume of the test area. The quantity and the concentration of bio-gas extracted with crude oil were relatively low. The alkane components of the production fluid were close to the fraction of the initial crude oil sample. With the activator injection of the second-round, the total amount of activator increased to 0.0492 PV, and the bio-gas produced after activation was enriched and aggregated with accumulating of the bio-gas in the previous round. The concentration of gas increased and the drive energy of the formation increased. A large amount of enriched bio-gas was intermixed with the superfluous dissolution and extraction phase of the crude oil with the injection pressure of 13 MPa (above the original formation saturation pressure of 7.5 MPa) and the residual oil in the reservoir was recovered [28].

Improvement effect of activator on reservoir profile

By comparing the changes in the injection profile, the combined action of the indigenous microbes after activation can be analyzed for the profile of the reservoir. From the experimental results of injection and production profile tests, activated microbial flooding improved the injection and production profile.

Before injection of active agent, N2-2-P40 well was stratified injected. The effective water-absorbing thickness of the main oil layer P I1-2 was 5.6 m and the relative water absorption was 83.15%, while the effective water-absorbing thickness of the poor oil layer P I_{3-4} water was 2.3m, the relative water absorption was only 16.85%. After the first round of the activator (March 2012) test and the second round (April 2013) test, the effective thickness of the injection profile increased from the original 7.9 m to 8.9 m and 10.2 m, respectively. The relative water absorption of the P I1-2 in the main oil layer decreased from 83.15% to 78.69% and 55.83%, respectively. The relative water absorption of the P I 3-4 in the poor oil layer increased from 16.85% to 21.31% and 55.83% and 44.17%, respectively. The water absorption of main reservoir was inhibited, the absorption capacity of poor oil layer has been further strengthened, and the producing status has been improved.

In addition, compared with the results of the production profile of the two wells before and after the injection of the activator, all the profile of the active section was activated. The reservoir thickness of the two wells was increased from 87.04 % and 89.19% to 100% (Fig. 7). Compared with the data before and after the test of N2-D3-P40 well, the two unused layers have been used. At the same time, water cut of the original layer has different degrees of decline; the effect of oil increment was obvious. The test was carried out in the 5th month after the end of the first round. The results showed that the unused intervals were used. Through the comprehensive analysis of the changes of the injection pressure and the injection profile, it can be seen that the "in situ" effect and the metabolites produced by the activated microbes have a certain profile control [29, 30].

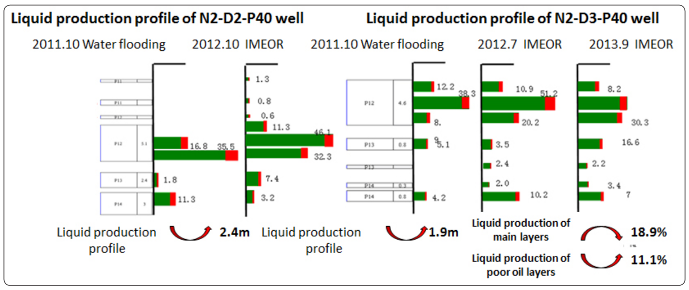

Figure 7: The test results of liquid production profile of production well

The change of the polymer flooding recovery

To compare the changes of oil production performances before and after the activation processes, the production data of 16 months before the experiment with obvious decreasing characteristics were obtained. The test began in early December 2011 and ended in October 2015. The oil production performance had a positive relationship with the activation process, with the oil production increasing and water content decreasing in the post-polymer flooded reservoir. During the test period, the amount of liquid produced from the first round increased from 482 t to 560 t, increased by 78 t / d, and increased from 480 t / d to 593 t / d, increased by 113 t / d during the second round. Water cut decreased from 96.1% in the first round to the lowest 93.9%, in the second round decreased from by the highest 97.7% to 96.2%. The daily oil production of the first round increased from 17.6 t / d to 31.5 t / d, and increased from 13.6 t / d to 21.2 t / d in the second round. In contrast, water cut of the whole block of the Nan East was always increasing, and the oil production decreased. The recovery degree of the test area was higher than that of the control area by 2.26%, see Figure 8.

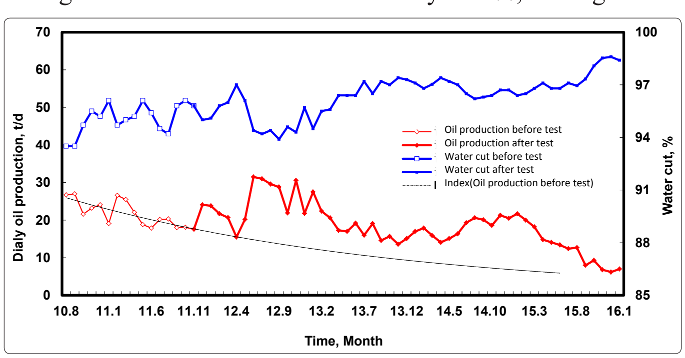

Figure 8: The curve of dynamic change of production before and after the activator injection

The total amount of injected activator solution of the two rounds test was 21,419 m^3, with the concentration of 1.34% and the total slugging volume of 0.0785 PV. By the end of 2015, the cumulative oil production was 20,524 t, excluding the natural decline and shutdown factors. The stage accumulated oil production was 6,243 t, the enhanced oil recovery rate was 3.93% (OOIP), and the input-output ratio was 1: 6.38.

Conclusion

The two round field trials of activating in-situ microbial community were carried out in an oil reservoir post polymer flooding. The trial test effect showed that the dominant bacteria of four production wells were directed activation, which showed a regular alternation with an increase of oil production. It contributes to production of bio-gas, leading to increasing of the injection pressure. A large amount of enriched bio-gas was dissolved into and mixed with crude oil, which brought increasing of the proportion of light components in the whole hydrocarbon of the recovered oil. The other effect was activated microbial metabolites productions formed bio-plugs, which benefits for improving of the absorption profile and the production profile. IMEOR can be implemented for effective enhancement of further oil recovery from polymer flooded oil reservoirs.

Acknowledgements

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