

The field pilot of microbial enhanced oil recovery in a high temperature petroleum reservoir

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Abstract

To evaluate the technical feasibility and effectiveness of improving oil recovery by microbial enhanced water-flooding techniques in high temperature petroleum reservoirs, a field project was initiated with the nature-occurring microorganisms and nutrient injected into an integrated, close Unit with temperature of 73 °C and salinity of 16,790 mg/L in 2001 in Dagang Oilfield, PetroChina. This paper presents the field design and the results of the field pilot with a discussion on characteristics of the reservoir and the performance of the microorganisms injected. Field results show that microorganisms can thrive, proliferate and move in the high temperature reservoir matrix, the positive effect of the bio-treatment first and mainly occurs in those production wells which have good connectivity with injection wells, and the indigenous microorganisms in the petroleum reservoir may also contribute to improving oil recovery due to the injection of nutrient. Results from this project suggest that microbial enhanced water-flooding technique has significant potential for enhancement of oil recovery in high temperature petroleum reservoirs.

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Extensive investigations on microbial enhanced oil recovery (MEOR) have been made in both the laboratories (Desouky et al., 1996; Stephens et al., 2000; Sui et al., 2001; Li et al., 2002; Wang, 2002) and field tests (Bryant and Burchfield, 1993; Zhang et al., 1996; Lazar, 1998; Feng and Chen, 1999; Nazina et al.,

1999; Wang et al., 2001) in the last decade. As to the investigation of field tests, although microbial enhanced water-flooding is believed to be one of the most promising technologies of enhancement of oil recovery, it is still applied under general reservoir conditions on a small scale. The major reason for this is that its technical feasibility and effectiveness in enhancement of oil recovery under difficult reservoir conditions (e.g. high temperature, etc.) have not been well documented by a little result from existing field tests.

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A microbial enhanced water-flooding project was conducted in Guan69 Unit at Dagang Oilfield in China by injection of microbial formulation with nutrient through injection wells in an ongoing waterflood reservoir to evaluate its technical feasibility and effectiveness in enhancement of oil recovery in high temperature reservoirs. The temperature and brine salinity of the tested reservoir are as high as 73 °C and 16,790 mg/L, respectively. And more importantly, this reservoir is well integrated, and production water from every production well was monitored independently during the project period, which makes it a convincing way to evaluate changes in oil production and the effectiveness of the microbial treatment. This paper presents the reservoir properties, design of the project and the results of the field pilot.

1. Description of the oil reservoir

The Guan 69 Unit in Dagang Oilfield is located in Hebei Province, China, and the distribution of the production and injection wells is shown in Fig. 1. This Unit is relatively close with a surface area of 1.19 km², OOIP (Original Oil In Place) of 192 × 10⁴ t. The oil-bearing formation is the Sandstone consisting of two layers as SaI and SaIII with the temperature, porosity, and permeability of 70 and 73 °C, 27.6% and 24.9%, 468 × 10^{−3} μm² and 259 × 10^{−3} μm², respectively, as outlined in Table 1. The composition of the formation brine is shown in Table 2.

The Guan 69 Unit was operated in primary production in 1984. Water flooding of the reservoir began in May 1988, and from then on, it has been

Table 1
Characteristics of the testing reservoir

Items	Parameters	
	SaI	SaIII
Formation	Sandstone	Sandstone
Buried depth (m)	1801.3–1850.0	1906.6–1960.0
Oil bearing area (km ²)	1.05	1.19
Original Oil In Place (OOIP), 10 ⁴ t	81	111
Average net pay thickness, (m)	5.3	6.7
Average permeability, 10 ^{−3} μm ²	468.4	259.2
Porosity, %	27.6	24.9
Original pressure (MPa)	17.78	18.89
Saturated pressure (MPa)	6.66	ND
Temperature (°C)	70	73
Original oil–gas ratio, m ³ /t	32	ND
Oil viscosity (underground), mPa · s	6	ND
Oil viscosity (surface, 50 °C), mPa · s	75.8	42.5
Oil density (surface), g/cm ³	0.8787	0.8841
Solidification point (°C)	37.7	37.9
Paraffin content (%)	27.4	28.1
Sulfur content (%)	0.097	0.078
Asphaltene content (%)	23.4	25.8

ND, Not Determined.

in continuous water flooding to the present time by the use of recycled water from the production water from this reservoir. In February 2001, the Unit covered 5 injection wells with injection volume of 357 m³/d, and 7 production wells with total oil production of 34.6 t/day. The cumulative oil production from this reservoir was about 53.8 × 10⁴ t with the oil recovery of OOIP of 22.61%, average water cut of 94.5%, and the cumulative water injection of 184.88 × 10⁴ m³. It was estimated that the recoverable oil in this Unit was about 70.0 × 10⁴ t by water flooding, which implies that about 77% OOIP has been recovered from the beginning of this project.

Table 2
The property of the formation water

Item	Na ⁺ +K ⁺	Ca ²⁺	Mg ²⁺	Cl [−]	SO ₄ ^{2−}	CO ₃ ^{2−}	TDS
Value (mg/L)	6075	298	87	9874	37	419	16790

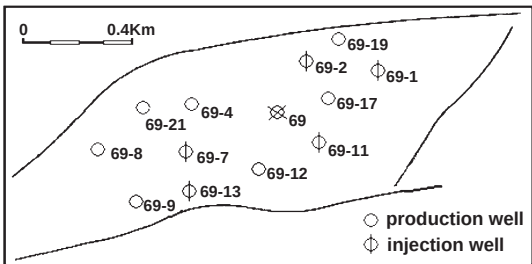


Fig. 1. The Map of Guan 69 Unit.

2. Laboratory experiments

2.1. Bacterial strains and the nutrients

Three microbial strains isolated from Dagang Oil-field were selected for the field project based on microbial compatibility tests of the strains with Guan 69 reservoir conditions. These strains were identified as *Arthrobacter* sp (A02), *Pseudomonas* sp (P15), and *Bacillus* sp (B24), respectively, according to their colony appearance, and physiology and cell morphology (Dong and Cai, 2001; Liang et al., 2004). A02 and P15 demonstrated a good capacity in degradation of oil, and B24 was more effective in reduction of the interfacial tension of oil and formation brine due to its production of biosurfactant from fermentation of crude oil.

A nutrient medium was developed based on growth behavior of the selected strains and the composition of the formation brine. The medium consists of crude oil (20 g/L), $\text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O}$ (0.8 g/L), KH_2PO_4 (0.45 g/L), Yeast extract (0.25 g/L), Peptone (0.1 g/L), NH_4Cl (2 g/L), Na_2EDTA (0.25 g/L), where Na_2EDTA was designed to inhibit the deposition caused by interaction of phosphates in the medium and the divalent cations in the brine. All the three strains exhibited vigorous growth in the medium when incubated under the simulated reservoir conditions in laboratory. When the medium is used for the field trial, the crude oil is not added in it for the existence of crude oil in the tested layer.

2.2. Performance of bacteria

2.2.1. Biosurfactant production

The biosurfactants produced by bacteria in broths were obtained and identified by the following procedures. Initially, each mixture of 5 ml viable microbe broth of strain A02, P15, or B24 with 5 ml oil from Well 69-8 and 200 ml medium with nutrient composition mentioned above contained in flasks was incubated at 73 °C with a water rotary shaker at 150 rpm for about 7 days. The resulting culture broth was then centrifuged at $6000 \times g$ for 20 min to remove residual oil and filtered with $0.22 \mu\text{m}^2$ filters to remove cells. The interfacial tensions of oil and filtrates were measured at 73 °C as 22.9, 22.2 and 23.7 mN/m for strain P15, B24 and A02, respectively, which indicates the

reduction of 25.9%, 28.2% and 23.3% compared with that of the blank sample and implies the production of surface-active compounds in the broths. Following it, the primary sample of biosurfactants in the filtrate at pH=6 adjusted with 6 mol/L H_2SO_4 was extracted by chloroform–methanol (2:1, *V/V*) and concentrated by distillation. The extract was redissolved in chloroform and then applied to a silica column which was successively eluted by hexane, chloroform and the mixture of chloroform and methanol (8:1, *V/V*), and the biosurfactant sample was obtained by distillation of the eluent. Finally, the biosurfactants were identified by the method of Thin Layer Chromatography (TLC), which shows that the biosurfactants produced by the selected strains fall under a kind of Glycolipids. The biosurfactant concentrations in cell-free broths of strain P15, B24 and A02 were measured by the colorimetric method (Dubois et al., 1956), which shows the values of 950, 1170 and 800 mg/L, respectively.

2.2.2. Fatty acid production

The cell-free broths were obtained and treated by the procedures same as that motioned above. The pH in the broths were measured as 5–6, which implies the production of some acids in the broths. For qualitative determination, the Gas Chromatography (GS) was applied (Ma et al., 1995), and the acetic acids and other short-chain fatty acids were found in the broths of the three strains. The titration with NaOH at a concentration of 0.10466 mol/L and phenolphthalein as the indicator was adopted to determine the concentration of the fatty acids in the broth, which indicates the values of 149.8, 135.0, and 175.5 mg/L in the broths of P15, B24, and A02, respectively.

2.2.3. Crude oil alternation

For evaluation of the effect of the strains on the crude oil, the mixtures of viable microbe broth (50 ml), the medium (200 ml), and crude oil from Well 69-8 in the Unit (50 ml) in conical flasks were incubated at 73 °C in a rotary shaker at 150 rpm for 7 days. The blank experiment was run in the same conditions but without inoculation. After incubation, the crude oil sample in the flasks was collected and electrically dehydrated in a pressurized tank, and its viscosity was measured with DV-III Brookfield Viscosimeter at 73 °C. The solidification point and the content of paraffin and asphaltene were measured by

the silica gel column chromatograph method (Zhang et al., 2000). The results are shown in Table 3.

2.2.4. Core flooding

For evaluation of oil displacement of the selected strains, core-flooding experiments were performed at 73 °C. The heterogeneous man-made core models with the size of $20 \times 4.5 \times 1.1$ cm, the permeability of $0.2\sim 0.6 \mu\text{m}^2$ and the porosity of 22~26% were used in experiments. The major procedures in the displacement are as follows: First, water-flooding of oil-bearing core with oil saturation of 65~70% was performed until no more oil was observed in the outlet of the core. Second, one pore volume of the bacterial suspension with a density of 1.5×10^7 cells/ml was injected into the water-flooded core, and followed by a 7-day shut-in period at 73 °C. Finally, water-flooding was again performed until no more oil was observed in the outlet of the core. The blank experiment was run in the same conditions but without injection of bacterial suspensions into cores. The results show that the incremental oil recoveries with bacterial suspensions of B24, A02 and P15 are 5.6%, 5.0% and 4.8% OOIP, respectively, compared with the blank core flooding results.

2.3. Detection of microorganisms in production water

For evaluation of the microorganisms in production water, the samples were collected at wellhead of the production wells in the tested reservoir in sterile glass bottles with rubber stoppers. These samples were serially diluted and viable counts were performed by the spread plate technique with LB (Luria–Bertani) medium. The incubation temperature was 73 °C. The

injected microorganisms were identified by the colony appearance developed on the LB medium and their physiology and cell morphology.

3. Field trial

3.1. Field-test design

The injection of the microbial suspension and the nutrient solution in the trial were initiated in March 2001 and completed in July 2001. The pattern of injection characterized by “nutrient-suspension-nutrient” was adopted. During the whole period of injection, the nutrient solution of about 350 m³/day was firstly injected for 3 days. The mixture of A02 and P15 suspensions of 210 m³ was then injected, and followed by a 10-day shut-in period of injection wells; the B24 suspension of 512 m³ was sequentially injected, and again followed by a 10-day shut-in period of injection wells. Following the injection of microbial suspension, the nutrient solution of about 350 m³/day was finally injected for 21 days. Before the injection, the microbial suspension was diluted by the nutrient solution to a microbial density of $1.8\sim 2.4 \times 10^7$ cells/ml from its original density about 3.0×10^8 cells/ml. Finally, the water injection was restarted as usual.

The injection pattern “nutrient-suspension-nutrient” mentioned above was designed based on the knowledge of the target reservoir conditions and the mechanism of enhancement of oil recovery by the selected strains in the reservoir. The primary section of nutrient solution designed is with the purpose to establish a necessary nutrient environment for the following injected microorganisms, while the last one is to supply microorganisms with more nutrients to maintain and stimulate the activities of injected as well as indigenous microorganisms in the reservoir. As for the sections of microbial suspension, the volume and sequence of injection were designed according to the performance of the selected strains. Strain A02 and P15 were first injected in expectation of removing asphaltene and paraffin deposited in pore throats near wellbore region due to their good capacity of biodegradation of oil; the strain B24 as the body section was then injected in the expectation to improve microscopic oil displacement efficiency by biosurfactants, and more importantly, a 10-day shut-in of the injection

Table 3
Microbial performances in change in properties of oil from Well 69-8

Species	Viscosity reduction (%)	Solidification point reduction (°C)	Paraffin content reduction (%)	Asphaltene content reduction (%)
A02	15.8	2.6	2.6	3.3
P15	14.0	3.1	3.3	2.5
B24	15.4	2.0	1.8	1.6

The original values of viscosity, solidification point, paraffin and asphaltene content of the tested oil sample are 22.8 mPa·s, 42.4 °C, 26.1% and 23.1%, respectively.

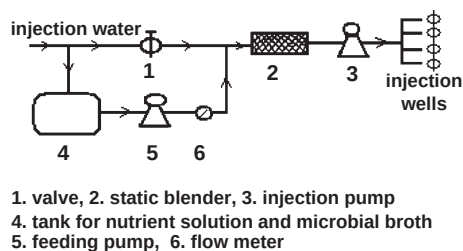


Fig. 2. Sketch of the bypass system for injection.

wells was followed with an aim to avoid microorganisms injected into the reservoir being excessively diluted by following injection and, therefore, to offer a time for their primarily proliferation in the reservoir.

The sketch of the bypass system for injection of microorganisms and nutrients is indicated in Fig. 2. As it shows in this figure that the microbial suspension or nutrient solution was first prepared in tank (4), and then mixed with water through a static blender (2) to achieve the designed concentration of microbial suspensions and nutrient solution, and finally injected by pump (3) into the target reservoir through injection wells.

3.2. Field results

Before the microbial water-flooding, the production performance and the related properties were monitored. During and after the microbial treatment, microorganisms in production water, the property of oil and production water, and the production performance in the Unit were also periodically monitored.

3.2.1. Growth and migration of microorganisms

According to the monitoring results of microorganisms in production water from all the 7 production wells in the Unit with a sampling interval of 15 days, no microorganisms same as the microbial species

Table 4

The surface tensions of the production water from the tested reservoir

Production wells	69-4	69-8	69-9	69-12	69-17	69-19	69-21
Baseline value (mN/m)	72.7	82.4	79.6	81.6	85.0	87.1	86.1
The minimum value (mN/m)	60.4	54.0	59.1	58.0	56.0	59.3	55.6
Reduction (mN/m)	12.3	28.4	20.5	23.6	29.0	27.8	30.5

Table 5

The oil property of Well 69-19

Item	Density (g/cm ³)	Viscosity (mPa·s)	Paraffin (%)	Asphaltene (%)
Before implement	0.8689	57.9	29.82	31.06
Aug, 2001	0.8671	54.1	27.84	30.54
March, 2002	0.8665	53.8	25.47	28.75

injected were detected in the samples collected before and in the beginning phase of the nutrient injection, but later, microorganisms in production water from Well 69-17 and Well 69-12 were first observed at a concentration of 2000–3000 cells/ml in two months; concentrations of microorganisms in production water from Well 69-9 and Well 69-8 were observed at a concentration of 6000–6800 cells/ml in five months. Subsequently, the microbial density was found in steady increase to its maximum about 1.6×10^5 cells/ml in about nine months. It is, therefore, reasonable to conclude that the injected microorganisms can proliferate in the target reservoir conditions. Furthermore, taking the well space (about 250 m) into consideration, the results suggest that the injected microorganisms may migrate through the reservoir matrix at a speed about 1.7–4.2 m/day.

In addition to microorganisms, the surface tensions of the production water were measured. It shows that the surface tension of the production water decreases due to biosurfactants produced by injected microorganisms and, probably, also by indigenous microorganisms in the reservoir. The maximum reduction in surface tension is 30.5 mN/m as shown in Table 4.

3.2.2. Change in properties of oil and gas

The change in properties of oil and gas from production wells were analyzed after bio-treatment,

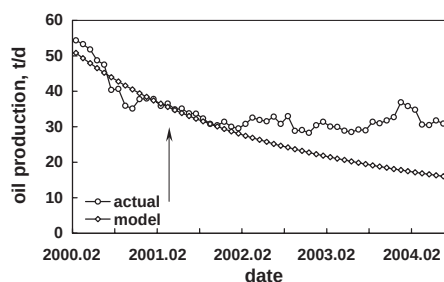


Fig. 3. Production curve of Guan69 Unit.

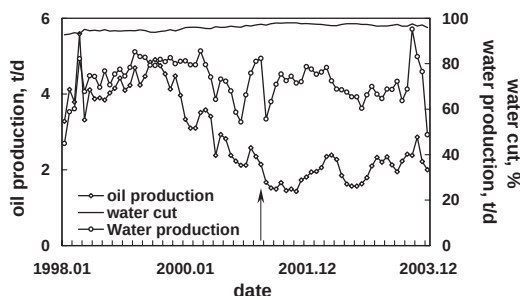


Fig. 4. Production curve of Well 69-9.

and a notable change in oil and connate gas was observed. The density, viscosity, paraffin and asphaltene content of crude oil from the Unit decreased as outlined in Table 5. The content of methane in the connate gas increased and that of carbon dioxide decreased. An example of change in the connate gas produced from Well 69-9 gives that the methane content increase from 85.4% to 90.2% and the carbon dioxide content decrease from 5.0% to 1.5%, respectively.

3.2.3. Increase in oil production

The oil production steadily increased after microbial water-flooding in the Unit. As it shows in Fig. 3 that, before and in the beginning phase of the injection, the oil production in the Unit decreased from 55 t/day in Jan. 2000 to 30.0 t/day in Sept. 2001, which implies a decline rate of 21%. However, this situation markedly changed six months later of the microbial treatment. By the end of July 2004, about 8700 t of additional oil was obtained compared with the predicted oil production by water flooding alone. All of the 7 production wells showed a positive response to the treatment, of which five Wells (69-9, 69-4, 69-17, 69-12 and 69-19) evidently increased in oil production. An example of the production performance of Well 69-9 is shown in Fig. 4.

4. Discussion

- (1) Microorganisms injected in reservoirs can thrive, migrate and finally form a gradient distribution in concentration in oil-bearings. Monitoring results show that the injected microorganisms are observed first and mainly in production

water from those production wells which have good response to water injection. The peak concentration of microorganisms in the production water is about 10^4 to 10^5 cells/ml. This concentration is much lower than that in injected suspensions with about 10^7 cells/ml, which implies that a falling gradient of microbial concentration may exist from injection wells to production wells.

- (2) Enhanced oil recovery in the experiment is due to the cumulative effect of injection of the nutrient medium, of the introduced bacteria, and of the microbial community of the stratum. The injected microorganisms play a part in oil extraction. According to the experimental results from both the laboratory and field trial, microbial activities and interactions of metabolic products with oil, brine and solid contribute to enhancement of oil recovery, among which the microbial degradation of oil and biosurfactants produced in situ (Mu et al., 2002) are major factors during microbial water-flooding. Other factors such as microbial modification of permeability are also believed to contribute to enhancement of oil production (Zekri and El-Mehaideb, 2003). Indigenous microorganisms in the tested reservoir also play a role in the change of gas contents and make a contribution to oil extraction. As mentioned above, a marked change of content of methane and carbon dioxide in the connate gas occurred after microbial treatment, which cannot be attributed to the activities of introduced microorganisms. It suggests that methanogenic bacteria existing in the target reservoir are activated by the nutrients and microorganisms introduced. Early researches (Borzenkov et al., 1997; Belyaev et al., 1998; Nazina et al., 1998, 2002) stated that methanogenic bacteria existed in the formation water in oil reservoirs, especially in long term water-flooded reservoirs and produced methane after activation by mineral salts supplied. In addition, other kinds of microorganisms existing in the oil-bearings might be activated as well and contributed to oil enhancement (Yakimov et al., 1997; Hao et al., 2004). The effective usage and contribution of indigenous microorganisms in petroleum reservoirs to

oil recovery should therefore be taken into consideration in the further studies.

- (3) Results from the project show that microbial water-flooding techniques have a potential of enhancing oil recovery in high temperature oil reservoirs.

Acknowledgments

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