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IMPLEMENTATIONS OF MICROBIAL TECHNOLOGY EXTEND LONGEVITY OF OIL FIELDS

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Abstract

Microbially enhanced oil recovery (MEOR) is a unique technique, which involves the injection of live organisms and/or nutrients into underground reservoirs to improve oil production and longevity of the field. Even though MEOR remains a relatively marginal technology, field trials of MEOR have been active in North America and Asia. This paper reports 16 MEOR field projects since 2000. According to the field cases surveyed, around 70% of treated wells demonstrated positive responses. Besides, all of the projects were profitable. Traditionally, high temperature and high salinity have prohibited field applications of MEOR. Among the field cases in this survey, MEOR has been tried in low-permeability formations, high-salinity reservoirs, high-temperature reservoirs, and heavy-oil fields. MEOR proved effective for challenging reservoir conditions with careful selection of microbes and proper project execution.

***Keywords**:* Microbe; Biosurfactant; Petroleum; Case study.

1. Introduction

It is estimated that more than 50% of original oil remains underground at field abandonment. Scientists and engineers have developed a few methods to improve oil production and field longevity. Routine water and gas injection are being carried out in the oilfields worldwide. Besides, enhanced oil recovery (EOR) methods are often employed to produce the residual oil that is difficult to mobilize. Commercial EOR methods include steam injection, polymer injection, and CO_2 injection [1-2].

Microbial enhanced oil recovery (MEOR) is a unique technique. In MEOR operations, live microorganisms and/or nutrients are injected into oil-bearing reservoirs. Bacteria and their metabolic products, such as biosurfactants and biopolymers mobilize the oil in the reservoir [3]. If favorable bacteria already reside in reservoirs, it is feasible to inject nutrients only. MEOR method has many distinguishable advantages. Natural products are usually harmless and environment-friendly. MEOR can be carried out in the field without major modification of present water injection facility. Besides, MEOR does not require high energy consumption [4].

However, MEOR did not gain widely-spread field applications worldwide. Some factors limited its field implementations. (1) Bacteria cannot survive under very high temperature. Therefore, MEOR is usually excluded from high-temperature reservoirs. (2) High salinity restricts the growth of microbes. In reality, many reservoirs contain high-salinity formation water. (3) The heavy components in crude oil, such as asphaltene and bitumen are toxic to microbes. (4) After microbes are injected into the reservoir, they have to compete with endogenous bacteria for prosperity. But sometimes the exogenous bacteria cannot win the battle. (5) Various chemicals are injected into the reservoir, including but not limited to acids, polymers, and surfactants. These chemicals may negatively impact microbial activities in the reservoir [5].

2. MEOR mechanisms

Certain bacteria are able to produce surfactants, polymers, gases, and solvents that contribute to the mobilization of oil in the reservoir. Many experimental studies were devoted to the understanding of MEOR mechanisms. The proposed MEOR mechanisms include a reduction in interfacial tension (IFT), permeability modification (or selective plugging), reduction in oil viscosity, alteration of wettability, and biodegradation [6]. This paper focuses on field applications of MEOR, rather than its mechanisms. Detailed descriptions of MEOR mechanisms can be found in the literature [7-8].

Certain bacteria produce biosurfactants that reduce oil-water interfacial tension [4,9-10]. The residual oil is held in porous rocks by capillary pressure, which is proportional to the interfacial tension (IFT) between oil and water. When IFT is reduced to a much lower value, residual oil begins to flow [11-12]. It was reported IFT reduced from 60 to 0.0012 N/m due to microbial metabolism [13].

A porous rock contains pores of various sizes. When undergoing water flooding, larger pores receive most of the injected water, while residual oil remains in small pores without being swept. When bacteria flow in reservoir rocks, they also tend to enter large pores. The bacteria themselves, or the biopolymers they generate, can plug the high-permeability zones with large pores, thus forcing injected water to sweep the oil in low-permeability zones [8].

Certain bacteria produce gas, organic acids and solvents in the reservoir [14]. Gas (such as methane and carbon dioxide) and solvents can dissolve in crude oil and reduce crude oil viscosity. It was observed that microbes could reduce heavy oil viscosity by more than 50% in the laboratory [11]. Lower oil viscosity leads to improved mobility ratio and oil recovery. In an experimental study, it was observed microbes produced large quantities of gas [15]. In reality, the produced gas can also increase the reservoir pressure, which leads to a higher production rate. Besides, some bacteria are able to degrade crude oil, especially the paraffin contents in crude oil [12]. When applied to the reservoir, bacteria can remove the paraffin deposit in the near wellbore region, thus improving permeability and production rate [16].

3. Field cases

Bacteria can be injected through either production well (also known as producer) or water injection well (also known as an injector). Most MEOR projects can be classified as huff and puff or microbial flooding, according to the methods of injection. For huff and puff operation, bacteria are injected into the reservoir through production wells. The wells are then shut in for some days before production resumes. For microbial flooding, bacteria reach reservoir through injection wells, then work their way to production wells. This section reviews MEOR field cases with relatively complete information.

3.1. North American fields

Five fields in Canada and USA operated by Husky Energy received an injection of nutrients only to activate indigenous microbes [12]. The reservoirs were of rather different rock and fluid properties, as seen in Table 1.

Table 1. Properties of the reservoirs that received a nutrient injection

Reservoir	Devonian, Alberta, Canada	Sparky, Alberta, Canada	Upper Topanga, California, USA	Hauser, California, USA	Sparky C, Alberta, Canada
Oil specific gravity	0.82	0.96	0.95	0.91	0.93
Depth (m)	1,056	600	1,585	1,650	661
Temperature (°C)	49	25	74	93	26
Porosity (%)	14-16	16	26	18-30	30
Permeability (md)	300	700	100-1000	10-100	600
Salinity (ppm TDS)	142,600	80,642	35,000	18,900	70,000
Watercut (%)	98	95	85	85	88

The Sparky field and Upper Topanga field produced relatively heavy oil, while the high-salinity Devonian field produced relatively light oil. From 2007 to late 2010, 35 producers and 30 injectors at the 5 fields received treatments, while 80% of wells showed positive responses. The producers saw a 205% increase in oil production combined. The field cases demonstrated MEOR was effective in treating both light and heavy oil reservoirs. Besides, MEOR was applied to high-temperature Hauser field with excellent results.

3.2. Mangunjaya field, Indonesia

The Mangunjaya field operated by Pertamina has been producing for 80 years, and oil recovery reached 40%, while water-cut reached 78% [18]. Water-cut is defined as the fraction of the volume of water in the produced liquid. The reservoir parameters are given in Table 2. In 2015, microbial huff and puff were conducted for two producing wells MJ-122 and MJ-155. The wells were first flushed with brine, then injected with microbes and nutrients, followed by a post flush with brine. Afterwards, the wells were shut in for 7 days. Three months after the treatments, water-cut dropped from 95% to around 50%, while the liquid production increase by 17%.

Table 2. Reservoir parameters of Mangunjaya field

Oil Viscosity (cP)	2.5	Reservoir pressure (MPa)	7
Porosity (%)	27.5	Reservoir temperature (°C)	50
Permeability (md)	120	Rock Type	Sandstone
Oil Saturation (%)	55	Pay zone thickness (m)	61
Reservoir depth (m)	170-365		

3.3. Daqing field, China

The Daqing field operated by CNPC was discovered in 1959. Implementation of water injection and polymer flooding injection lead to good recovery factor. The field produces relatively light oil under moderate reservoir temperature. The favorable reservoir conditions make the field a good candidate for MEOR. Microbial huff and puff were conducted on 518 wells in 10 blocks at Daqing, which leads to 63,386 tonnes of incremental oil production [19].

Bohetai block is a tight (i.e., low-permeability) reservoir with permeability ranging from 1 to 50 md. In 2002, huff and puff operations were conducted for thirteen production wells with a mixture of five different strains [20]. After injection, wells were shut in for 7 days. After production resumed, the viscosity of produced fluid dropped from 101 cP before the treatment to 57 cP afterwards, the wax content reduced by 1-5%, while the oil-water interfacial tension reduced by 40%. Ten wells responded positively to treatment. Water-cut of the block dropped from 61% to 44%. It was estimated 2,138 tonnes of extra oil were produced. The well with the highest permeability yielded the best output. The daily oil rate increased from 0.4 tonnes before the treatment to 5.2 tonnes afterwards. In 2003, four wells were chosen for the second round of bacterial huff and puff, while the results were still excellent.

After the successful trials at Bohetai block, Chao50 block received a bacterial injection from June 2004 to February 2005 [21]. It is a tight reservoir with the properties presented in Table 3.

Table 3. Parameters of Chao50 block

Area of block (km^2)	2.25	Average porosity	0.17
OOIP (tonnes)	1,667,000	Average permeability (md)	25
Reservoir depth (m)	989	Dead oil viscosity (cP)	94.3
Reservoir thickness (m)	7.9 to 9.5	Water-cut	95%
Reservoir temperature (ºC)	55		

Traditionally, MEOR was recommended to permeability higher than 50 md. However the average permeability was only 25 md for this reservoir. The block involved 10 producers and 2 injectors. *Brevibacillus brevis* and *Bacillus cereus* were chosen for injection [22]. Their sizes were around 0.8×1.4micron and 0.4×1.0micron, respectively. The average pore throat size was 2.3 micron. Therefore, microbes were able to move through the pores. This assumption was supported by high concentrations of microbes in the produced fluid.

After injection of 250 tonnes of bacterial fluid, seven producers responded positively to microbial injection. Liquid output increased from 957 tonnes/month before the treatment to 1,456 tonnes/month. Monthly oil production climbed from 361 to 843 tonnes, while water-cut dropped from 95% to 38.6%. It was estimated that 13,600 tonnes of incremental oil were produced. Oil parameters also improved. The oil viscosity dropped by 20% to 76 cP. The paraffin content dropped by 5% to 7.6%. The interfacial tension dropped by 14% to 0.04 N/m. It was observed the producers that were located near the injectors demonstrated better results. This trial proved MEOR could be effective even for very tight formation. After the successful trail, microbial EOR spread to 60 wells in the block, while 43 wells saw positive feedback with 9,175 tonnes of additional oil production.

3.4. Shengli field, China

Shengli field operated by Sinopec was discovered in 1961. The field features complex geologies and diversified reservoir characteristics. The field has produced more than one billion tonnes of oil so far. Water flooding, polymer flooding, and steam flooding are common practices in the field. MEOR also attracted much attention at Shengli. Microbial huff and puff have been conducted on 1640 wells, which contributed to 219,000 tonnes of additional oil production [23]. Some typical MEOR field cases at Shengli are introduced here.

The Luo801 block was producing heavy oil, as shown in Table 4. Rock expansion and solution gas resulted in an oil recovery of only 11%. After the liberation of solution gas, the oil became more viscous. In 1994, the viscosity of produced oil from well-805 was 189 cP. In 1998, oil viscosity climbed to 725 cP. The oil production from the block decreased from 472 to 200 tonnes/day. The pilot started in 1998 [24] when bacteria were injected through 4 injectors that are connected to 11 producers. Before the treatments, daily oil production from the block was 200 tonnes. After bacterial flooding, oil production climbed to more than 300 tonnes/day. It was estimated that around 43,500 tonnes of extra oil were produced.

Table 4. Parameters of Luo801 block

Area of the block (km^2)	1.6	Reservoir temperature (ºC)	80
Reservoir depths (m)	1,680 to 1,800	Salinity of formation water (mg/L)	9,794
Porosity	0.281	Pour point of oil (ºC)	26 to 38
Permeability (md)	215.2	Density of oil (g/mL)	0.932

Zhan3 block has received water injection since 1989. Oil recovery reached only 25% after 22 years of water injection, while the water-cut was as high as 92%. The block contains 13 producers and 5 injectors. The reservoir parameters are given in Table 5. Three production wells received a nutrient injection, but no bacteria was introduced [25]. The wells were shut in for one week before production resumed. Wells saw an increase in oil production (3.4 to 10.4 tonnes/day), and a decrease in water-cut (93% to 88%). The successful pilot leads to expanded trials at the field. Till December 2014, totally 5,997 tonnes of nutrients has been injected, resulting in 27,000 tonnes of additional oil output [23].

Table 5. Parameters of Zhan3 block

Area of block (km^2)	1.5
OOIP (tonnes)	2,820,000
Reservoir depth (m)	1,240 – 1,360
Reservoir temperature (ºC)	63
Porosity	0.30
Permeability (md)	800 – 1,000
Oil API gravity	11.8
Dead oil viscosity (cP)	1,885
Salinity of formation water (mg/L)	8,900

3.5. Xinjiang field, China

The Xinjiang field is located in west China and operated by CNPC. Fourteen wells at Xinjiang field received bacterial treatments from September 2007 to August 2008 [26]. The block produced heavy oil with reservoir parameters given in Table 6. Laboratory work demonstrated the selected microbes could emulsify heavy oil and significantly reduce oil viscosity. For the field trial, the wells were first treated with steam to remove wax and debris. After bacterial fluid was injected, the wells were shut in for 2-3 days before resuming production. Twelve wells showed positive responses, producing 1,535 tonnes of extra oil totally.

Table 6. Reservoir data for a trial block in Xinjiang

Wells depths (m)	92 to 610
Reservoir temperature (ºC)	15 to 29
Porosity (%)	20.5 to 25
Permeability (md)	334 to 676
Dead oil viscosity at 50ºC (cP)	228 to 1,135

In 2014, the 7-Zhong block was selected for nutrient injection, without receiving exogenous bacteria. The block involves 4 injectors and 11 producers. The block's OOIP was 719,000 tonnes, and oil recovery reached 41% before the treatment. The nutrient contained sugar, sodium nitrate, and ammonium phosphate. Nutrient injection lasted 1.5 years, with total injection volume equivalent to 0.1 PV [27]. Three months after the treatments started, all 11 wells showed positive feedback, while the number of bacteria in the produced water escalated to 10^8/mL. Total oil production climbed from 14 tonnes/day before the treatment to 41 tonnes/day afterwards. Water-cut dropped from 90% to 81%. Additional oil production was estimated at 21513 tonnes [28].

3.6. Liaohe field, China

The Liaohe field is located in Northeast China, operated by CNPC. Prior to implementation of MEOR at Liaohe field, laboratory work was conducted on two bacterial strains. It was discovered that the strains produced surfactants that could emulsify heavy oil. The bacteria grew best under 37 to 55ºC. Field trial started in September 2005, when thirteen producers on Jin45 and Qian12 blocks in Liaohe field began to receive bacteria injection [29]. Prior to bacterial treatments, the blocks had been steam flooded for more than ten years, but the effect of steam already weakened. The wells produced heavy oil with a viscosity of over 5,000 cP at the surface. The wells were injected with bacteria then shut in for 7 to 9 days. After the wells were back on, the production rates soon began to rise. Till February 2006, twelve wells showed positive response and produced 2,511 tonnes of additional oil after the treatments. The trial proved MEOR was more cost-effective than steam flooding for the treated wells. For well Jin-45, producing one tonne of oil with steam flooding cost 863 CNY, while with bacteria the cost was only 339 CNY.

Table 7. Parameters of Leng43 block

Average porosity	20.5%
Average permeability (md)	725
Reservoir depth (m)	1,410-1,650
Reservoir temperature (ºC)	48
Oil saturation before treatment	60%

The Leng43 block at Liaohe field produces very heavy oil. The crude oil density was 0.97 g/mL, and its viscosity was between 9,620 and 43,000 cp at 50ºC. The salinity of formation was relatively low at 5,435 mg/L. The reservoir parameters are given in Table 7. Five producers were selected for microbial huff and puff [30]. Before the treatment, the five wells had received a steam injection, but with poor production. The wells first received nutrient fluid through the casing-tubing annulus, followed by a mixture of bacteria and nutrient, finally a slug of nutrient. The wells were then shut in for 7 days. After production resumed, four wells saw increases in oil production and decrease in water-cut by 10%. Additional 530 tonnes of oil was produced. For the fifth well, its liquid production increased significantly, but the oil rate was almost the same as before.

Jing35 block is a shallow heavy oil reservoir. The low reservoir temperature hinders the flow of heavy oil. As a result, the recovery factor was only 4.3% till 2012. Three cycles of microbial huff and puff were conducted on 6 production wells in 2013. Three bacteria strains were selected: *Geobacillus stearothermophilus, Geobacillus thermodenitrificans*, and *Pseudomonas aeruginosa.* Till June 2014, 5 out of 6 production wells reported increases in production, with 1,344 tonnes of incremental oil accumulatively. The effects of microbial treatments lasted more than 10 months [31].

3.7. Baolige field, China

The Baolige field, located in Inner Mongolia and operated by CNPC, occupied 20.8 km^2 where 78 injectors and 169 producers were spaced. The field parameters are favorable for implementation of MEOR, as seen in Table 8. A large-scale MEOR project was started in May 2012. Nutrients and two strained were injected into the reservoir through injection wells. After 60 days, field oil production increased from 820 t/day to 920 t/day, while water-cut dropped from 78.5% to 65.8%. Beside, oil viscosity reduced from 188 cp to 80 cp. The field received 4 cycles of injection totally, followed by routine water flooding. Around 85% of all production wells reported higher production rates after microbial treatments. The oil production stabilized around 900 t/day till early 2016. By estimation, additional oil production reached 210,000 tonnes accumulatively [32]. In order to enhance microbial activities, nutrients and bacteria were added to produced water at water treatment facilities, before the produced water was re-injected into the reservoir [33].

Table 8. Reservoir data of Baolige field

Area of block (km^2)	20.8
OOIP (tonnes)	35 million
Reservoir temperature (ºC)	50
Porosity	0.18
Permeability (md)	144
Dead oil viscosity (cP)	188

4. Summary and discussions

This case study verifies the proposed MEOR mechanisms. Most field cases reported increases in injection pressure soon after bacteria injection. This can be attributed to the plugging of pore throats by microbes, production of biopolymers, or production of gases. It was also observed that the injection pressure began to decline at a certain stage of the projects. This is possibly because the surfactants produced by bacteria reduced interfacial tension between oil and water, which was also observed at the surface. Besides, the viscosity of produced oil decreased for many projects. After microbial treatments, many wells' paraffin issues also eased. This proved that the bacteria degraded crude oil to some extent. However, most projects did not experience a significant increase in gas production.

However, MEOR indeed involves more uncertainties than steam flood or polymer flood. In the past, most MEOR field cases were conducted for reservoir temperatures below 60°C [34], because most bacteria cannot prosper at high temperatures. Besides, the high salinity in deep oil and gas reservoirs impacts bacterial growth negatively. Moreover, injected bacteria have to compete with the endogenous microbes in the reservoir. If the injected slug is not adequate, microbes cannot prosper. Thus, the effect of MEOR is compromised.

The field cases in this survey are summarized in Table 9. Commercial MEOR projects were carried out at Daqing field, and Baolige field, where the reservoir temperature was mild and the salinity was moderate. However, MEOR has been tried in more challenging reservoirs, i.e., high temperature, high salinity, low permeability, and heavy oil. For some field cases, reservoir temperature reached 93ºC, salinity as high as 142,600 ppm, oil viscosity as high as 43,000 cp at the surface, and reservoir permeability as low as 25 md. Nevertheless, MEOR achieved good successes under such challenging conditions. Moreover, all of the projects proved profitable.

Table 9. Summary of MEOR field cases

Project	Reservoir features	Success rate
Five fields in Canada and USA	Four fields with heavy oil One field with high salinity One field with high temperature	80%
Mangunjaya	Low temperature; Low Pressure	100%
Bohetai	Tight reservoir	77%
Chao50	Tight reservoir	70%
Luo801	Heavy oil; Moderate permeability and salinity;	Not reported
Zhan3	Heavy oil; High permeability; Moderate salinity;	33%
Xinjiang	Low temperature; Moderate permeability;	86%
7-Zhong	Large injection volume	100%
Jin15 and Qian12	Heavy oil	92%
Leng-43	Heavy oil	80%
Jing-35	Heavy oil	83%
Baolige	Favorable reservoir conditions; Large-scale field application;	85%

According to the field experiences, the criteria for MEOR applications can be extended with proper selection of bacteria and project execution. First of all, the selected strains must be able to prosper under the reservoir conditions. Then they mobilize oil by producing biosurfactants or degrading crude oil. This step requires a lot of efforts on identification, incubation, and evaluation of strains in the laboratory. Second, the injected slug should be adequate, so that the exogenous bacteria can successfully build a colony in the reservoir. When only nutrients are injected, the number of nutrients should be adequate to support the long-term metabolism of bacteria. In reality, the injected slugs were often very small, usually less than 0.05 PV. According to field experiences in China, the slug size should be at least 0.05 PV with a concentration of 2% [35]. Thirdly, the wells and facilities should be carefully prepared prior to MEOR operations. The facilities involved should be treated with steam to remove debris and undesirable microbes, so that the injected bacteria can safely reach the reservoir. For the projects in China, usually a slug of polymer or nutrient was injected in front of the bacteria in order to provide protection for the injected bacteria. Above all, MEOR has been implemented commercially in North America and China, which indicates the maturity of this technique.

5. Conclusion

(1) For the MEOR projects conducted in North American and Asia, we observed an increase in injection pressure, a decrease in IFT, and a decrease in oil viscosity. These phenomena verified the proposed MEOR mechanisms, including permeability modification (or selective plugging), IFT reduction, and oil degradation. (2) Most of the MEOR projects in this survey achieved good success rates. More than 70% of the wells treated by microbes showed positive responses. (3) All MEOR projects were profitable. (4) The field cases proved MEOR effective for challenging reservoir conditions, i.e., high temperature, high salinity, and heavy oil.

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