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Experiences of microbial enhanced oil recovery in Chinese oil fields

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ABSTRACT

Microbial enhanced oil recovery (MEOR) is a unique technique but remains relatively marginal. However, trials of MEOR in Chinese oil fields are still active. This paper briefly discusses the mechanisms of MEOR, then reports more than twenty MEOR field projects carried out in China since 2000. Those field cases were not well known due to language barrier. The cases were implemented over months or even years. According to field experiences in China, MEOR achieved good success rates, with around 70% of treated wells showing positive responses. Besides, all of the projects were profitable. Traditionally, high temperature and high salinity have been obstacles for field applications of MEOR, but the field cases in China extended the method to more challenging reservoir conditions. MEOR has been tried in tight 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.

1. Introduction

Oil recovery factor is affected by many factors, including rock properties, fluid properties, wettability, and reservoir drive mechanisms (Ahmed, 2010). Even after primary recovery and secondary recovery processes, large amount of residual oil is held in reservoir rocks by capillary force. It is estimated that more than 50% of original oil remains underground at field abandonment (Gao et al., 2014). Besides, it is likely that the large oil fields have been discovered. Future discoveries will be smaller and more challenging to produce. Tertiary recovery methods, or enhanced oil recovery (EOR) methods are often employed to produce the residual oil that is difficult to mobilize with routine water and gas flooding. Most common EOR methods include thermal recovery, chemical flooding, and miscible gas injection, such as CO_2 flooding (Alvarado and Manrique, 2010).

Microbial enhanced oil recovery (MEOR) is a unique technique. In MEOR operations, live microorganisms and/or nutrients are injected into reservoir. Bacteria and their metabolic products, such as biosurfactants and biopolymers can mobilize the oil in reservoir (Perfumo et al., 2010). 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. It is easy to carry out in the field, because no modification of present water injection facility is required. MEOR does not require high energy consumption (Geetha et al., 2018).

However, MEOR did not gain widely spread field applications around the globe. Some factors did limit its field implementations. (1) Bacteria can not survive under very high temperature. Therefore MEOR is not considered for high-temperature reservoirs. (2) High salinity restricts growth of microbes. However many reservoirs contain high-salinity formation water. (3) The heavy components in crude oil, such as asphaltenes 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 can not win the battle. (5) All kinds of chemicals are injected into the reservoir, including but not limited to acids, polymers and surfactants. Those chemicals may negatively impact microbial activities in the reservoir (Safdel et al., 2017).

2. MEOR mechanisms

Certain bacteria are able to produce surfactants, polymers, gases and solvents that contribute to mobilization of oil in reservoir. Many experimental studies were devoted to the understanding of MEOR mechanisms. The proposed MEOR mechanisms include reduction in interfacial tension (IFT), permeability modification (or selective plugging), reduction in oil viscosity, alteration of wettability, and biodegradation (Sen, 2008). This paper focuses on field applications of MEOR, rather than its mechanisms. Detailed descriptions of MEOR mechanisms can be found in literature (Gao et al., 2009; Patel et al., 2015).

Certain bacteria produce biosurfactants that reduce oil-water interfacial tension (Banat et al., 2010; Hung and Shreve, 2001; Geetha et al., 2018). The residual oil is held in porous rocks by capillary pressure,

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which is proportional to the interfacial tension (IFT) between oil and water. When IFT is reduced to a much lower value, residual oil starts to flow. Chinese researchers also observed significant IFT reduction by microbes (Ju et al., 2002; Yi and Deng, 2008; Liu and Tao, 2009). It was reported IFT reduced from 60 to 0.0012 N/m due to microbial metabolism (Ju et al., 2002).

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 (Patel et al., 2015).

Certain bacteria produce gas, organic acids and solvents in the reservoir, (Liu et al., 2011). Gas (such as methane and carbon dioxide) and solvents can dissolve in crude oil and reduce crude oil viscosity. It was observed that microbes can reduce heavy oil viscosity by more than 50% in laboratory (Yi and Deng, 2008). Lower oil viscosity leads to improved mobility ratio and oil recovery. In an experimental study, it was observed microbes produced large quantities of gas (Lei et al., 2009). In reality, the produced gas can also increase the reservoir pressure, which leads to higher production rate.

Besides, some bacteria are able to degrade crude oil, especially the paraffin contents in crude oil (Liu and Tao, 2009). When applied to reservoir, bacteria can remove the paraffin deposit in the near wellbore region, thus improving permeability and production rate (Wang et al., 2007).

3. Field cases

Bacteria can be injected through either production well (also known as producer) or water injection well (also known as injector). Most MEOR projects can be classified as huff and puff or bacteria 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 some typical MEOR field cases with relatively complete information. A few field cases had to be discarded due to lack of key information.

3.1. Fuyu field cases

Fuyu field is located in the Jilin province in Northeast China. The reservoir data are given in Table 1. The field is characterized by mild temperature and low water salinity, which are favorable conditions for bacteria. From 1992 to 2001, 250 wells were selected for huff-puff injections (Di et al., 2005). The selected wells were producing very low oil rates (less than 1 tonne/day; 1 tonne equals 1000 kg) at high water-cuts (above 85%). The wells were injected with 150–300 m^3 of fluid containing 1% bacteria plus 10% nutrient, then shut in for 10–20 days. Among the 250 wells treated, 195 wells responded positively and produced 18704 tonnes of additional oil accumulatively. After treatments, not only water-cut reduced, paraffin and scale issues also eased. The production of CO_2 increased significantly, which indicated bacteria produced large amount of CO_2 in the reservoir.

Table 1
Reservoir properties of Fuyu field.

OOIP (tonnes)	1.31×10^8
Reservoir depth (m)	300–500
Reservoir temperature (°C)	28–33
Pay zone thickness (m)	30–60
Reservoir permeability (md)	100–300
Reservoir porosity	0.22–0.26
Oil viscosity (cp)	21–24
Salinity of formation water (mg/L)	4000–6000
Water-cut	Above 85%

3.2. Daqing field cases

The Daqing field was discovered in 1959. Implementation of water flooding and polymer flooding achieved good recovery factor. The field produces relatively light oil under moderate reservoir temperature. The reservoir conditions make the field a good candidate for MEOR technique. According to a survey, microbial huff and puff was conducted on 518 wells in 10 blocks at Daqing, which lead to 63,386 tonnes of incremental oil production (Wu et al., 2013). Till the end of 2012, microbial flooding was carried out on 45 injection wells connected to 144 production wells in 11 blocks. Microbial flooding recovered 56,837 tonnes of extra oil (Le et al., 2015).

3.2.1. Sabei block

Polymer flooding achieved great results in Daqing field. Field experiences demonstrated polymer flooding yielded 10–12% increase in oil recovery. However, about 50% OOIP still remains in the reservoir even after polymer flooding. The Sabei block was flooded with polymer since 1995. Oil recovery reached 52.5% in April 2003, while water-cut reached 95% (Guo et al., 2006a). The limited information of reservoir properties is given in Table 2. Two injectors and six producers were placed on five-spot pattern with a distance of 250 m between injector and producer.

A trial was conducted at Sabei block to test feasibility of MEOR after polymer flooding. Two types of microbes were sourced from field waste water. They are referred to as TP-1 and TP-2 bacteria (Wang et al., 2006). Laboratory work revealed different biological properties for the two strains, as shown in Table 3. Core-flooding tests showed injection of bacteria could reduce rock permeability and improve oil recovery by 4% (Guo et al., 2006b).

Injected of bacterial fluid was initiated in August 2004. Totally 15,030 m^3 of bacterial fluid was injected into the two wells, equivalent to 0.015 PV (pore volume). High concentration of bacteria was observed in produced fluid. The permeability of the block dropped to 330 md. As a result, the injection pressure at injector wellhead increased by 1 MPa. This indicated the bacteria blocked some of the high-permeability channels in the reservoir.

Before treatment, a high-permeability zone existed in the injector B25—P16 that absorbed 87% injected water into the well. After bacterial treatment, the zonal water intake reduced to 25%. Similarly for a zone in injector B24—P26, its water intake reduced from 100% to 37%. Some zones did not take water before the treatment, but absorbed high percentage of injected water afterwards. This indicated the growth of bacteria inside reservoir affected flow paths of injected water.

Among the 6 producers, 3 wells showed positive response. The daily oil production from the 3 wells increased by 16 tonnes, while the water-cut dropped by 4%. Totally 1300 tonnes of extra oil were produced. Bacterial treatment yielded best results in well B25-21. Its water-cut decreased by 4.8%, while 800 tonnes of additional oil were produced from the well accumulatively. This trial proved MEOR can further improve recovery even after the field has been flooded with polymer.

3.2.2. Bohetai block

Bohetai block is a tight 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 (Li et al., 2003b).

Table 2
Properties of Sabei block.

Reservoir area (km^2)	0.24
OOIP (tonne)	5.125×10^5
Reservoir permeability (md)	570
Pay zone thickness (m)	10 to 13