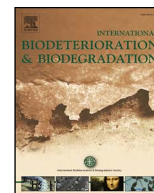
International Biodeterioration & Biodegradation 127 (2018) 247–253

Contents lists available at ScienceDirect

International Biodeterioration & Biodegradation

journal homepage: www.elsevier.com/locate/ibiod



A pilot study on large-scale microbial enhanced oil recovery (MEOR) in Baolige Oilfield

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ARTICLE INFO

Keywords:
Large-scale study
Microbial enhanced oil recovery
Microbial strains
Water flooding

ABSTRACT

Industrial application of microbial enhanced oil recovery (MEOR) has been hindered by a lack of large-scale data-based guidelines for process design and operation. In the present work MEOR was investigated in both laboratory and large-scale oilfield studies. Six microbial strains were initially isolated from Baolige Oilfield in China. Laboratory based investigation showed that all six strains were able to decrease the oil viscosity. Two mixtures of strains exhibited greater reduction effects, i.e., 35% and 56%, respectively. The optimal nutrient concentration was found to be 1.0%. The mixtures of strains tested in laboratory core flooding based MEOR also confirmed their greater MEOR performance, i.e., MEOR levels of 9.1% and 13.2%, respectively, compared to that of any single strain ranging from 7.0% % to 8.7%. Using the strain mixture that had been selected under the laboratory based conditions, the pilot field study achieved a significant MEOR: 210,000 tons of crude oil produced over 43 months from 169 production wells. The research results obtained in this work including both laboratory and field studies can be potentially applied in other oilfields with similar geological and physical conditions, for large-scale MEOR process design and operation.

1. Introduction

Water flooding is a commonly used method for secondary oil recovery. Water is injected into the oil field to physically displace and sweep the oil to the production wells (Taware et al., 2017). However, there remain challenges in using water flooding techniques. In particular, variable permeability, uncontrollability of fluidic conditions, and undesirable interface properties contribute to inefficient recovery (Taware et al., 2017). As a result, conventional, water-flood oil recovery operation often leaves one half to two-thirds of the oil in the reservoir within the complex capillary network (Brown, 2010; Gao and Zekri, 2011; Siegert et al., 2014; Song et al., 2015). Therefore, there has been tremendous effort in developing alternative and more efficient strategies to improve oil recovery. Among the alternative technologies in development, microbial enhanced oil recovery (MEOR) is regarded as an economic and environmentally friendly tertiary oil recovery, which has attracted much attention in recent years (Gao and Zekri, 2011; Lazar et al., 2007; Le et al., 2015; Nazar et al., 2011; Safdel et al., 2017; Sen, 2008). However, in spite of its potential benefits, MEOR is currently still not widely applied to industrial applications, that is largely attributed to a lack of sufficient field-test data, especially from large-scale tests to support design for industrial processes (Safdel et al., 2017), and regarded as a significant road blocker.

In principle, MEOR uses microorganisms (either indigenous or exogenous) and their metabolites to enhance oil recovery. It is generally understood that the MEOR process is facilitated either by metabolites or by biosurfactant production. Metabolites such as extracellular polymeric substance (EPS) selectively block high-permeability zones, leading to selective plugging and diverting the water into lower permeability zones. Biosurfactants, produced *in situ* reduce oil viscosity and interfacial tension between oil-water-rock interfaces. This reduced interfacial tension increases residual oil mobilisation (Armstrong et al., 2015; Kryachko et al., 2013; Le et al., 2015; Sen, 2008). It has been demonstrated that microbes and nutrients injected into a reservoir can stimulate the *in situ* production of MEOR agents such as biosurfactants, biopolymers, acid and gas (Dhanarajan et al., 2017; Joy et al., 2017; Saxena, 2015; Whitby and Skovhus, 2010).

At present, the majority of studies on MEOR have been conducted in laboratory-scale. Pilot studies in oilfields have mostly involved a small number of wells (ranging from two to dozens) (Amani, 2015; Armstrong et al., 2015; Bao et al., 2013; Fulazzaky et al., 2015; Huang et al., 2014; Kryachko and Voordouw, 2014; Sen, 2008; Youssef et al., 2013). Additionally, theoretical analysis and numerical modelling have been used to assist design and optimize MEOR operations (Liu et al., 2014; Nielsen

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https://doi.org/10.1016/j.ibiod.2017.12.009
Received 21 October 2017; Received in revised form 24 December 2017; Accepted 25 December 2017
Available online 10 January 2018
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et al., 2014; Sivasankar and Kumar, 2014; Spirov et al., 2014). However, it is challenging to use laboratory-scale models to closely simulate actual oilfield geophysicochemicals conditions. The dramatic difference in geometry scale and system complexity, that significantly limit the relevance of predictions based on laboratory microcosm studies (Brown, 2010). This unpredictability can become a huge risk factor for industrial operation failure, normally associated with significant cost. To date, there have been very few attempts to conduct large-scale applications in oilfields for MEOR.

Therefore, the aim of the present work was to address this research gap by conducting a large-scale, long term and systematic field test as a pilot to verify the feasibility of MEOR for industrial application, and ultimately provide data-based guidelines for further industrial design and operations.

Prior to the field test, six facultative anaerobes were isolated from the local production fluid. The performance of individual isolates and mixed cultures were first examined in laboratory. Parameters investigated included: growth rate, gas production rate and interfacial properties. The MEOR effect was then investigated with a laboratory-scale core flooding model.

The filed test was carried out in four fault-blocks (namely, B19, B38, B48 and B51) in Baolige Oilfield for this pilot study. The surface area of the four fault-block is approximately 20.8 km^2 with original oil in place of 35×10^6 tons. This investigation included results from the oilfield's 78 injection wells and 169 oil production wells.

2. Materials and methods

2.1. Materials

All chemicals and reagents were obtained commercially and used as received. The biochemical reagent kits were purchased from Beijing Leadman Biochemical Limited, China. Glucose, peptone, yeast extract, urea, ammonium sulphate, potassium dihydrogen phosphate, magnesium sulphate and sodium chloride were of analytical grade and purchased from Tianjin Tian Da Chemical Factory, China. Other reagents used in this study were also of analytical grade, and the water was deionized.

Instrument included multi-function core flow experimental device (LDY-III, Nantong Yi Chuang Experimental Instruments Co., Ltd.), Spectrophotometer (UV-2550, Shimadzu), Haake viscosimeter (RS-300, Thermo Scientific), Spinning Drop Interface Tensiometer (TX-500C, Kenuo of the United States), and Surface Tensiometer (A801S, Kenuo of the United States).

The strains used in this study were isolated from the production fluid of Baolige Oilfield. They were *Bacillus subtilis*, *Arthrobacter*, G. *subterraneus*, *Pseudomonas aeruginosa*, *Bacillus licheniformis* and *Rhodococcus* sp., and were named HB3, IV, H, Z-2, LC and JH, respectively.

2.2. Methods

2.2.1. Isolation and characterization of bacterial strains

To obtain the high efficiency strains for MEOR, experiments were performed to enrich and isolate high efficient strains from the produced fluids of oil wells in Baolige oilfield. Because the average temperature of the target reservoir was 50 °C, all the experiments were carried out at this temperature.

The brine (20 mL) and crude oil (10 g) were transferred to a 500 mL conical flask containing 120 mL medium consisted of (wt.%): glucose 2.0%, peptone 0.05%, yeast extract 0.05%, urea 0.05%, ammonium sulphate 0.05%, potassium dihydrogen phosphate 0.5%, magnesium sulphate 0.02%, and sodium chloride 0.01%, and incubated at 50 °C, 180 rpm for 5 days. The choice of the concentration range was based on the previous feasibility investigation (data not shown). To isolate strains capable of biosurfactant production, the samples with good emulsifying effect on crude oil were selected for the further isolation. Taking 0.1 mL culture broth spread on LB agar plates and incubated at 50 °C for 48 h. The pure colonies were obtained by repetitive streaking on solid LB agar medium.

A loop of biomass was scraped off the agar plate, suspended in 20 mL distilled water to lyse by boiling for 10 min and freezing for 5 min. The supernatant was used as the template for PCR after centrifugation. Phylogenetic analysis based on 16S rRNA gene sequences were performed according to Wu et al. (2013).

2.2.2. Batch growth conditions

Batch growth experiments were performed, following the published procedure (Xia et al., 2012), using 100 mL LB medium at different temperatures (20–60 °C) at 200 rpm. After 48 h incubation, the optical density at 600 nm (OD_{600}) was measured using the spectrophotometer. The results are averages of three independent experiments.

2.2.3. Determination of surface tension and interfacial tension

The surface tension of the supernatant fluid was measured by the Wilhelmy plate method with a surface tensiometer DST-100 (SEO, Korea) at 25 °C. The interfacial tension of crude oil/water systems were determined using a Spinning Drop Video Tensiometer SVT20 (Dataphysics Instrument Gmbh, Germany). During measurement, the supernatant of the fermentation broth was filled in the capillary, then a drop of crude oil was added to the supernatant, and the interfacial tension was measured when the temperature was raised to 50 °C (Sakthivel et al., 2015). Each result was the average of three determinations.

2.2.4. Emulsifying activity

The emulsifying activity of fermentation broth was determined at 25 °C, as follows: the supernatant liquid was mixed with equal volumes of crude oil for 2 min, and then it was settled at room temperature for 24 h. The emulsification index (E_{24}) was calculated as the ratio of the height of the emulsion layer to the total height of the mixture (Dastgheib et al., 2008).

2.2.5. The determination of bacterial density

The samples of produced fluids from oil wells were diluted serially to desired concentrations. The bacterial density were then counted by the flat colony counting method (Baron et al., 2006). Each dilution was plated in triplicate on a nutrient agar plate and incubated at 37 °C for 24 h. The number of CFU at each dilution rate was counted after incubation and the average CFU/ml was determined.

2.2.6. Core flooding tests

Prior to field applications, core flooding tests were conducted in laboratories, following a commonly used procedure (Gao et al., 2013).

(i) Core tube filling and water saturation. A 50 cm long core tube (inner diameter, 2.5 cm) was used. It was filled with silica sand (80, 150 and 200 mesh, mixed as desired) by mechanical loading. After sand loading the core tube was under vacuum conditions for 6 h in order to remove air. Saline solution was then pumped into the core tube. The total volume of saline solution pumped into the core tube and the pressure difference between the inlet and outlet of the core tube were recorded.

Based on the measurement, the porosity Φ and permeability K of the core tube were calculated.

$$\Phi = \frac{PV}{V_T} \times 100\% \tag{1}$$

$$K = Q\frac{\mu_w L}{\Delta PA} \tag{2}$$

where PV is pore volume and V_T is the total volume of the core tube. Q is the displacement rate (mL/min), and L and A are the length and

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