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Enhanced oil recovery from low permeability dolomite cores using biosurfactant produced by a *Bacillus mojavensis* (PTCC 1696) isolated from Masjed-I Soleyman field

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ABSTRACT

A *Bacillus mojavensis* strain (PTCC 1696) which was isolated from an Iranian oil field was used to produce a lipopeptidic biosurfactant. The surface activity measurement with De Nouy ring detachment method showed that this biosurfactant is able to reduce the surface tension of the media and interfacial tension between aqueous phase and n-hexadecane to 26.7 and 0.1 mN/m respectively. The core flooding tests were carried out to evaluate oil recovery from carbonate reservoirs by this lipopeptidic biosurfactant. These tests were conducted at reservoir conditions using low permeability dolomite cores, live crude oil and reservoir formation brine. The experiments showed that the biosurfactant-assisted waterflooding method can be considered as a technique for oil recovery from carbonate formations. The results obtained in this study showed the potential of the biosurfactant produced by *Bacillus* strains for enhanced oil recovery even from low-permeability carbonate reservoirs.

1. Introduction

The oil recovery by conventional water flooding process is not known as an effective technique in the oil-wet; especially fractured reservoirs. Theoretically, displacement of the residual oil through the porous media depends on the capillary number which is defined as follows:

$$N_C = \frac{\text{Viscous force}}{\text{Capillary force}} = \frac{\mu\nu}{\xi} \quad (1)$$

where N_C is the dimensionless capillary number, μ [cp] is the viscosity, ν [cm/h] is the frontal velocity and ξ [mN/m] is the interfacial tension between displacing and displaced fluids.

The oil recovery from porous media could be increased only when the capillary number of the oil displacing fluid significantly increased. In fractured carbonate reservoirs, surfactants can improve oil displacement from the matrix blocks into the fractures by lowering capillary forces (Austad et al., 1998; Standnes and Austad, 2003; Zhang et al., 2006). Recently, the oil recovery from carbonates by surfactants has been interestingly considered (Austad et al., 1998; Ayirala et al., 2006; Babadagli, 2006; Babadagli et al., 2005; Gupta and Mohanty, 2007; Standnes and Austad, 2000a, 2000b; Zhang and Austad, 2006). Almost all surfactants currently in use are originally derived from the petroleum. Therefore in spite of increasing oil prices in recent years, economy of the surfactant injection is still critical (Babadagli, 2006; Babadagli et al., 2005). During past few decades, many efforts have been done to investigate oil displacement by surfactant producing bacteria (Banat, 1995; Batista et al., 2006; Daoshan et al., 2004; Horowitz et al., 1990; Joshi et al., 2008; Maudgalya et al., 2005; Yakimov et al., 1995; Youssef et al., 2007). These efforts provided potential bacteria and effective biosurfactants comparable to synthetic surfactants useful for enhanced oil recovery. These microbial surfactants can be produced from inexpensive and renewable resources (Makkar and Cameotra, 1997; Nitschke and Pastore, 2006; Rodrigues et al., 2006) such as sugar cane molasses with a cost lower than $ 0.5 per liter (Portilla-Rivera et al., 2009). The economy of the commercial production of these materials is affected by the downstream processing costs which are about 60% of total production cost of many biological products (Mukherjee et al., 2006). Thus, the required purity of the biosurfactants plays an important role on economy of their commercial applications. Typically, costs of the biosurfactants can be changed from $ 10 per mg for purified surfactin (98% purity) in biomedical research to the $ 2–4 per kg in the emulsion formulations for tank cleaning/oil recovery applications (Bognolo, 1999). Therefore, crude or impure biosurfactants which can be obtained at the initial stages of recovery process can be used for environmental and oil recovery applications in future. In addition, these applications are eco-friendly, nontoxic and biodegradable. Therefore these materials compared to synthetic and toxic chemicals that are dangerous to the oil workers and environment can be led to cost saving on a long time.

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The biosurfactants can be used alone (Maudgalya et al., 2005) or in combination with synthetic surfactants for oil recovery applications (Daoshan et al., 2004).

In the present work, unlike other researches regarding to oil recovery from sandstone cores using biosurfactant injection (Daoshan et al., 2004; Maudgalya et al., 2005), the dolomite cores were used and core floods were also simulated to reservoir conditions with actual reservoir fluids such as live crude oil and reservoir formation brine. Here, we have investigated efficiency of a biosurfactant produced by a *Bacillus mojavensis* strain (PTCC 1696) which we had isolated in previous works (Ghojavand et al., 2008a, 2008b); for oil recovery from dolomite cores.

2. Materials and methods

2.1. Core preparation

We have obtained a type of carbonate rock from outcrop of Masjed-I Soleyman (MIS) oil field at southwest of Iran. Chemical composition of the rock sample was analyzed by X-ray fluorescence spectrometer (Philips X' Unique II). The presence of the 10% (w/w) MgO and 40% (w/w) CaO in the rock composition showed that the prepared rock was a dolomite rock. Core samples were prepared by cutting rock samples into cylindrical specimens with 3.86 cm diameter. The core samples were washed thoroughly with standard cleaning procedure using toluene in the soxhlet device and dried in an oven at 120 °C overnight (Babadagli, 2006). Each of the cores was encased in Viton rubber sleeves and was placed inside stainless steel core-holder. The core was then evacuated and flushed with brine. The absolute permeability of the cores was determined by Darcy's law:

$$K = \frac{Q}{A}\frac{\mu L}{\Delta P} \quad (2)$$

where K [D]is the absolute permeability, Q [cm^3/s] is volumetric flow rate, A [cm^2] is area of core cross section, μ [cp] is the viscosity, L [cm] is core length and ΔP [atm] is the pressure drop of the fluid along the length L. The absolute permeability of these cores varied from 0.19 to 0.57 mD. Properties of the cores that are used in this study are given in Table 1.

2.2. Reservoir fluid properties

All experiments were carried out using crude oil and formation brine which were taken from the MIS reservoir. Gas and dead oil samples were taken from well-head separator. Live crude oil was prepared by recombining the gas and oil according to the gas–oil ratio of the reservoir. The properties of the live crude oil used in this study were gas–oil ratio of 17.6 Sm^3/Sm^3, formation volume factor of 1.065 and oil gravity of 36 API. At reservoir temperature (42 °C), viscosity of the live crude oil which was measured by Jefri High-Pressure Fluid Viscometer (DB Robinson) was 1.80 and 1.91 cp at 3445 and 4134 kPa pressures respectively. Composition of the live crude oil is listed in Table 2. The MIS formation brine which has been used for irreducible water saturation was taken at depths of 433 to 526 m sub-sea of several oil wells in the MIS oil reservoir. The composition of major ions in the reservoir brine is shown in Table 3. The NaCl salinity of the brine is 240 (g/l). The brine has total dissolved solid content (TDS) of 294 (g/l) and pH of 8.0.

Table 1
Properties of the carbonate (dolomite) cores used in this study.

Core name	D (cm)	L (cm)	K (mD)	φ (%)
MIS-4-1	3.86	6.81	0.22	12.51
MIS-4-3	3.86	7.55	0.41	12.67
MIS-4-4	3.82	7.46	0.57	12.12

Table 2
Composition of the reservoir live crude oil.

Reservoir oil (live oil)			
Composition	Mole%	Composition	Mole%
N_2	0.307	C_9	10.09
C_1	8.582	C_{10}	5.683
CO_2	0.767	C_{11}	2.961
C_2	0.814	C_{12}	2.402
H_2S	0.88	C_{13}	2.056
C_3	0.781	C_{14}	1.408
iC_4	0.394	C_{15}	1.058
nC_4	1.545	C_{16}	0.567
iC_5	2.14	C_{17}	0.394
nC_5	2.998	C_{18}	0.268
C_6	7.795	C_{19}	0.251
C_7	10.36	C_{20}^+	23.51
C_8	11.99		

Molecular weight = 152.79 g/g mole.

2.3. Displacing fluid formulations

Oil production from very low permeability dolomite cores was investigated using various displacement fluids. Waterflooding was carried out using sea water sample taken from the Persian Gulf. The sea water analysis showed presence of following items: TDS of 45 (g/l), NaCl salinity of 38 (g/l), and pH of 8.0. The composition of major ions in this sea water sample is given in Table 3. Biosurfactant-mediated oil recovery tests were either carried out using a mixture of the biosurfactant and co-surfactant or a mixture of the biosurfactant, co-surfactant and a polymer. The biosurfactant produced by a *Bacillus* strain (PTCC 1696) was used in all experiments at concentration of ten times higher than critical micelle concentration (CMC). Type and amount of the polymer and co-surfactant which were used in all experiments of this study were selected based on the Oklahoma MEOR group (Maudgalya et al., 2005). Therefore, the co-surfactant of 2, 3-butanediol (Merck, Schuchardt, and 85662 Hohenbrunn, Germany) at concentration of 10 mM and the polymer of partially hydrolyzed polyacrylamide (Qingdao Great Chemical Inc., China) at concentration of 1000 ppm were used. The addition of a low molecular weight alcohol (2, 3-butanediol) as co-surfactant to the biosurfactant solution caused to alter the biosurfactant behavior and raised the optimal salinity of the biosurfactant (Lelanne-Cassou et al., 1993; Salter, 1978). In addition, co-surfactants are employed in the oil displacing system to aid surfactants in solubilizing hydrocarbons, usually by stabilizing surfactant/hydrocarbon microemulsions (Knickerbocker et al., 1979; Martel et al., 1993). The polymer of partially hydrolyzed polyacrylamide was added to the biosurfactant solution as a mobility control agent to prevent dissipation of the oil bank before it reached the effluent end.

Table 3
Composition of the formation brine taken from the MIS oil reservoir and sea water sample taken from the Persian Gulf used in this study.

Formation brine		Sea water	
Major components	Concentration (g/l)	Major components	Concentration (g/l)
Na^+	101.625	Na^+	14.96
K^+	0.75		
Ca^{+2}	6.56	Ca^{+2}	0.5
Mg^{+2}	2.6112	Mg^{+2}	1.3
Cl^-	163	Cl^-	23.1
SO_4^{-2}	18.21	SO_4^{-2}	–
CO_3^{-2}	0.008	CO_3^{-2}	0.03
HCO_3^-	0.129	HCO_3^-	0.1
Total nitrogen	0.013		