Fuel 183 (2016) 501–511

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

A novel method to model and characterize in-situ bio-surfactant production in microbial enhanced oil recovery

Pooneh Hosseininoosheri [a,*], Hamid R. Lashgari [b], Kamy Sepehrnoori [c]

[a] 200 E. Dean Keeton, Stop C0304CPGE, CPE 4.172, Austin, TX 78712-1587, United States
[b] 200 E. Dean Keeton, Stop C0304CPGE, CPE 3.136, Austin, TX 78712-1587, United States
[c] 200 E. Dean Keeton, Stop C0304CPGE, CPE 4.104A, Austin, TX 78712-1587, United States

ARTICLE INFO

Article history:
Received 8 February 2016
Received in revised form 2 March 2016
Accepted 7 June 2016

Keywords:
Biosurfactant
Microbial
Enhanced oil recovery
Reservoir simulation
Reservoir modeling
Interfacial tension
Multiphase flow
Porous media

ABSTRACT

Capillary force is an important factor that limits the efficiency of water flooding by trapping the oil in porous media. High capillarity is caused by high interfacial tension (IFT) between oil and water that leads to a high residual oil saturation. Surfactants are widely used to reduce IFT and significantly mobilize the entrapped oil. However, the surfactants that are injected into a reservoir to lower the IFT several orders of magnitude may not be cost effective. Microbial enhanced oil recovery (MEOR) process may potentially address a cost effective alternative to surfactant flooding. In the MEOR process, nutrients and natural bacteria are injected into a reservoir and both indigenous and injected microorganisms are able to react and then generate biosurfactants based on in-situ reactions.

Modeling of microbial enhanced oil recovery requires coupling kinetics transport with local equilibrium transport in the presence of the surfactant phase behavior model (i.e. Hand's rule). In general, reservoir simulators do not model relative chemical reactions that consider the effect of essential environmental parameters such as temperature, salinity, and pH.

The main objective of this work is to present first order Monod kinetic equations as a function of temperature, salinity, and pH, which control the biodegradation reactions and microbial growth rate. Furthermore, the impact of biosurfactant adsorption, maximum growth rate, and nutrient concentration are systematically investigated. Also, the effects of environmental factors are implemented in a four-phase chemical flooding reservoir simulator (UTCHEM). Subsequently, the simulator is used to history match a coreflood experimental data to model the contribution of cited parameters on oil recovery.

Results show that in-situ biosurfactant generation rates can be thoroughly modeled based on environmental factors IFT can be reduced in a similar manner as surfactants. Simulation results show 10–15% incremental oil recovery using in-situ biosurfactant compared to waterflooding. Moreover, based on the simulation results, nutrient concentration, salinity and temperature are found to be the most significant parameters influencing oil recovery, whereas pH has insignificant effect.

The understanding of in-situ biosurfactant generation in a MEOR process, implementing a new environmental model into the simulator, and investigating of various parameters influencing the efficiency of the MEOR process are the key findings of this work.

1. Introduction

The challenge to increase oil recovery from reservoirs exists to come up with an alternative and cost-effective recovery process [8]. Primary production and secondary recovery operations improve only one-third to one-half of the original oil in place in reservoirs [15,17,34]. The high interfacial tension (IFT) between water and hydrocarbon that results in high capillary forces is largely responsible for trapping the hydrocarbon in the porous matrix [2,16,33]. In order to mobilize the entrapped hydrocarbon, it is crucial to use a method which can reduce the interfacial tension between hydrocarbon and water to several orders of magnitude [5,33]. The use of surfactants is a choice, but a high concentration of surfactant is needed to form a large amount of micelles which leads to the high costs of using chemical surfactants for enhanced oil recovery.

Microbial Enhanced Oil Recovery (MEOR) is an alternative tertiary oil recovery technology that employs the use of microbial

* Corresponding author.
E-mail addresses: poonehhosseini@utexas.edu (P. Hosseininoosheri), hlashgari@utexas.edu (H.R. Lashgari), Kamys@mail.utexas.edu (K. Sepehrnoori).

http://dx.doi.org/10.1016/j.fuel.2016.06.035
0016-2361/

Nomenclature

A	aqueous phase electron acceptor concentration (ML^{-3})
$\bar{A}$	electron acceptor concentration in attached biomass (ML^{-3})
S	aqueous phase substrate concentration (ML^{-3})
$\bar{S}$	substrate concentration in attached biomass (ML^{-3})
A	aqueous phase electron acceptor concentration (ML^{-3})
$\bar{A}$	electron acceptor concentration in attached biomass (ML^{-3})
X	aqueous phase (unattached) biomass concentration (ML^{-3})
$\bar{X}$	attached biomass concentration; mass of attached cells per volume of aqueous phase (ML^{-3})
β	surface area of a single microcolony (L^2)
k	mass transfer coefficient (LT^{-1})
$\mu_{\max}$	maximum specific growth rate (T^{-1})
m_c	mass of cells in a single microcolony
E	mass of electron acceptor consumed per mass of substrate biodegraded
ρ_x	biomass density; mass of cells per volume of biomass (ML^{-3})
V_c	volume of a single microcolony (L^3)
Y	yield coefficient; mass of cells produced per mass of substrate biodegraded
K_S	substrate half – saturation coefficient (ML^{-3})
K_A	electron acceptor half – saturation coefficient (ML^{-3})
k_{abio}	first – order reaction rate coefficient (for abiotic decay reactions, T^{-1})
b	endogenous decay coefficient (T^{-1})
t	time (T)
$S_{lr}^{low}, S_{lr}^{high}$	residual saturations for phase l at low and hight rapping numbers (L^3/L^3)
N_{Tl}	trapping number of phase l
$\sigma_{l\acute{l}}$	IFT between displacing and displacement phases (MT^2)
k_{rl}^{o}	end point relative permeability of phase l
$k_{rl}^{o^{high}}, k_{rl}^{o^{low}}$	end point relative permeability of high and low IFT for phase l
n_l	exponent of relative permeability of phase l
n_l^{high}, n_l^{low}	exponent of relative permeability of high and low trapping numbers for phase l
C_{hl}	concentration of component h in phase l (L^3/L^3)
R_{l3}	solubilization ratio
C_{SE}	effective salinity
$\hat{C}_k$	adsorbed concentration of component k (L^3/L^3)
a_{31}, a_{32}	surfactant adsorption parameters
b_k	surfactant adsorption parameter
k	permeability (L^2)
T	temperature (T)
C_{sal}	reservoir salinity (L^3/L^3)
T_{opt}	optimal temperature (T)
C_{sal}^{opt}	optimal salinity at which microbe can grow (L^3/L^3)
pH_{opt}	optimal pH at which microbe can grow
$T_{\min}$	minimum temperature at which microbe can grow (T)
$pH_{\min}$	minimum pH at which microbe can grow (T)
$T_{\max}$	maximum temperature at which microbe can grow
C_{sal}^{max}	maximum salinity at which microbe can grow (L^3/L^3)
Subscripts	
h, k	component number
l	phase number

metabolites to improve the recovery of remaining oil from depleted reservoirs [10]. MEOR has several advantages compared to other enhanced oil recovery (EOR) processes by being potentially cost-effective even at relatively low crude oil prices, and being easy to implement in the field [6,7,31,34]. Also it can be environmental friendly, since microbial products are biodegradable and have low toxicity [15,21]. This EOR method can be performed through several mechanisms that are complicated and include multiple biochemical processes [11,21,25,26]. Microbes contribute to EOR in two ways: (a) they grow in reservoir rock and generate biosurfactants, biopolymers, acids, gases and other biochemical to recover trapped oil; and (b) they can increase the sweep efficiency of the process by selectively plugging the high-permeability zones [30].

Biosurfactant generation by microorganisms constitutes an effective mechanism to recover a large amount of the remaining oil from mature oil fields [1,15,22,30]. Biosurfactants are a heterogeneous group of surface-active molecules produced by a wide range of microorganisms. Having both polar and nonpolar portions enables the biosurfactants to partition at water-oil or water-gas interfaces and thus contribute positively to improve oil recovery by reducing interfacial or surface tensions [3,6,7,35]. Furthermore, biosurfactants can reduce the IFT by altering the wettability of reservoir rock to displace more oil from the capillary networks [30]. These properties make them one of the most promising advanced methods to recover a substantial proportion of the residual oil [3,13,35]. However, biosurfactant generation has been viewed with skepticism, since it is not clear how biosurfactants can be generated in sufficient quantities to mobilize entrapped oil [34,35]. Therefore, it is extremely important to study and evaluate different parameters that affect the biosurfactant production.

Many experimental works and modeling studies have been performed to determine the feasibility of MEOR. All studies reported an enhancement in oil recovery; however, most of them have not considered the effect of environmental factors. The lack in quantifying the effect of reservoir conditions on such a process creates uncertainty in predicting the performance of MEOR process.

This work investigates a biosurfactant-dominated MEOR process. For this purpose, nutrients and specially selected natural bacteria are injected into a synthetic reservoir. We assume that both indigenous and injected microorganisms can generate in-situ biosurfactant. The generated biosurfactant mobilizes oil by emulsification and IFT reduction.

1.1. Experimental work

ZoBell presented the first experimental results explaining the main mechanisms responsible for oil mobilization in porous media by microbial metabolites [36]. He described and patented processes by which microbial products including gases, acids, solvents, biopolymers, biosurfactants, and biomass improve oil releasing from sandpack columns in laboratory tests. Updegraff and Wren [32] patented an MEOR method involving the injection of microorganisms which can convert economic substrates to the agents of oil recovery.

The Mobil Research Laboratory in the Libson performed the first field test using MEOR in 1954. In the 1960s to 1970s, numerous field trials were conducted in Eastern Europe. The injection of