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Full Length Article

Influence of bio-clogging induced formation damage on performance of microbial enhanced oil recovery processes

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A R T I C L E I N F O

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A B S T R A C T

In-situ microbial enhanced oil recovery (MEOR) is an economical and environment friendlier technique to recover the trapped oil from oil reservoirs. However, its oil recovery efficiency is reduced significantly due to the occurrence of formation damage induced by bio-clogging. Hence, to improve the oil recovery efficiency, it is required to understand the effects of bio-clogging on *in-situ* MEOR processes, which could assist in development of suitable well stimulation strategies. Thus, in the present study, the influence of bio-clogging induced formation damage on *in-situ* MEOR processes has been numerically investigated for different Reynolds number (Re) by varying the microbial slug injection rate (Q_n) and for different biosurfactant yield (Y_{PX}) values. It is found out that with lowering of Re and increasing the Y_{PX} values, the bio-clogging and sweep efficiency increases, while the swept length decreases. The study determines the critical time and critical distance to perform well stimulation technique, in order to completely evade the detrimental effects of bio-clogging on residual oil recovery. The results revealed that in the absence of bio-clogging: (a) the original oil in place (OOIP) recovered could be increased by 106% and 24.5% by flooding at $1Re$ and $3Re$ respectively from its respective bio-clogging OOIP levels; and (b) the final OOIP recovered at $1Re$ is nearly equivalent to that of $3Re$. Finally, the study concludes that the oil recovery during *in-situ* MEOR could be enhanced significantly at relatively lower cost by: (a) regularly performing the well stimulation at the prescribed critical time and for critical distance; and (b) selecting microbes with higher Y_{PX} values and flooding them at relatively lower Re. Thus, the present study would assist in: selection of suitable Q_n, microbe and nutrients; and efficient planning of well stimulation operations to improve the oil recovery.

1. Introduction

In-situ microbial enhanced oil recovery (MEOR) is a tertiary method to recover the trapped residual oil from oil reservoirs that were left unrecovered after the application of primary and secondary recovery methods [1]. In *in-situ* MEOR technique, either indigenous or non-indigenous microbes are injected into the reservoir, which undergoes metabolic activity by consuming the nutrients, and produces metabolites (biosurfactants, biopolymers, gases, alcohol) within the reservoir, which in turn, recovers the trapped oil within it [1,2]. During the implementation of *in-situ* MEOR technique, the formation damage (reduction in reservoir rock's permeability and porosity) occurs due to microbial clogging/bio-clogging process, in addition to other formation damage processes that includes asphaltene or paraffin deposition, invasion of drilling mud into reservoir rock and fines migration [3]. In comparison with other chemical EOR techniques, *in-situ* MEOR is a cost effective, easy to implement and environment friendlier technique [4,5]. Though *in-situ* MEOR technique inherits several merits, the performance of *in-situ* MEOR process during its field implementation is expected to be retarded mainly by formation damage that occurs due to the clogging of both injected and indigenous microbes near the injection well [2]. This bio-clogging process reduces the rock's hydraulic properties (porosity, permeability) and subsequently restricts the fluid flow within the reservoir [2,6], and hence it could not consider to be insignificant. The growth of microbes that leads to bio-clogging process is prevented by treating the reservoir with biocides (anti-microbial agent), which is one of the well stimulation technique [3]. Thus, understanding the influence of bio-clogging induced formation damage on the performance of *in-situ* MEOR processes would greatly assist in the development of better strategies for well stimulation and for efficient implementation of *in-situ* MEOR technique in the oil fields to achieve the maximum oil recovery.

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Earlier, MEOR modelling studies [7,8] had quantified the reduction in porosity and permeability for different microbial concentration and microbial kinetic parametric values at various time scales. Later, Ezeuko et al. [3] modelled the bio-clogging process and numerically investigated the influence of biocide treatment on bio-clogging process. Subsequently, Nielsen et al. [9] numerically modelled the influence of different filtration models on water saturation and on oil recovery during MEOR. However, there is a limited understanding on the influence of formation damage induced by bio-clogging on *in-situ* MEOR processes that includes multiphase fluid flow, microbial transport, biosurfactant production, interfacial tension (IFT) reduction, change in Capillary number, recovery of residual oil and original oil in place (OOIP) recovered. Particularly, the information on the influence of injection rate and microbial kinetic parameters related to microbial and biosurfactant yield on bio-clogging, and its subsequent effect on *in-situ* MEOR processes is very limited. Moreover, during implementation of *in-situ* MEOR technique, to mitigate the detrimental effects of formation damage due to bio-clogging, the following strategic decision-making questions remains largely unanswered that includes: (a) whether well stimulation is required to enhance the reservoir permeability? If so, when it should be carried out following the microbial injection? and how frequently, it should be done in a typical oil reservoir in terms of number of Pore Volume Injected (PVI) for different injection rates? (b) in order to achieve effective well stimulation, what would be the spatial extent from injection well that must be stimulated for applying different injection rates and by using microbes with different kinetic parametric values?

In this context, the present study aims: (a) to numerically model the *in-situ* MEOR processes involving formation damage due to bio-clogging; (b) to analyse the sensitivity of injection rate and biosurfactant yield ratio values on bio-clogging induced formation damage, and subsequently to quantify its effect on the performance of *in-situ* MEOR processes; and (c) to propose strategies that would mitigate the detrimental effects of bio-clogging induced formation damage on the performance of *in-situ* MEOR processes, and thereby, to improve the recovery of residual oil. Thus, the outcomes of present study would help to select a suitable injection rate and suitable microbes with specific kinetic parameters well ahead of MEOR implementation, and subsequently, to efficiently plan the extent of well stimulation operations required to improve the oil production.

2. Physical system and governing equations

2.1. Physical system

Fig. 1 shows the present physical system which is a water wet Berea sandstone rock sample, and it is initially saturated with the water and residual oil. The microbial slug used in the present study is a mixture containing water, non-indigenous *Pseudomonas* sp. microbe and nutrients (sucrose and ammonium sulphate). The *in-situ* MEOR process is initiated by horizontally flooding the rock with the microbial slug along its west face with injection flow rate of Q_n (m^3 s^{-1}) at n ($n = 9$) injection points which are placed 0.5 m apart from each other, and with the total injection flow rate of Q_t ($Q_t = nQ_n$). The assumptions involved in the present study are as follows: (a) The reservoir is homogenous, experiencing non-isothermal, horizontal and laminar flow; (b) temperature and salinity of the reservoir and injection fluid are considered to be same, and the change in pH due to dissolution of CO_2 in the water is also assumed to be marginal, hence the influence of change in temperature, salinity and pH on microbial kinetic processes and its associated oil recovery is assumed to be insignificant; (c) biosurfactant is the only bioproduct involved in oil recovery mechanism, because *Pseudomonas* sp. majorly produces biosurfactants as its bioproduct [1].

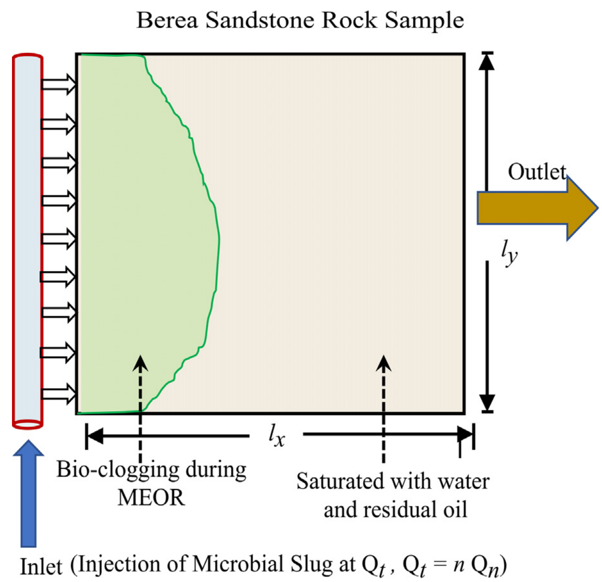

Fig. 1. Schematic of present physical system showing bio-clogging in rock sample during in-situ MEOR application.

2.2. Governing equations for in-situ MEOR processes with bio-clogging

The *in-situ* MEOR processes is mathematically presented through Eqs. (1)–(15) [7,10–14]. Because of microbial flooding, the water (wetting phase) pressure [P_w (Nm^{-2})] distribution causes the water to flow at velocity of u_w (ms^{-1}) within the reservoir [Eqs. (1)–(6)]. The terms: ϕ, k, P_{ce} and P_c represents porosity, absolute permeability, entry capillary pressure and capillary pressure respectively; ρ_i, μ_i, S_i and k_i are density, viscosity, saturation and relative permeability of fluid phase i (where, i = water, oil) respectively. S_{or}, S_{wir} and A_r are residual oil saturation, irreducible water saturation and rock's cross-sectional area respectively.

$$\phi c_t\left(\frac{\partial P_w}{\partial t}\right) = \nabla.\ [(\lambda_w + \lambda_o)\nabla P_w] + \nabla.\ (\lambda_o \nabla P_c) - \nabla.\ [(\rho_w g \lambda_w + \rho_o g \lambda_o)\nabla z] \tag{1}$$

$$\lambda_w = \frac{kk_{rw}}{\mu_w};\ \lambda_o = \frac{kk_{ro}}{\mu_o};\ k_{rw} = (S_w^*)^{\frac{2+3\tau}{\tau}};\ k_{ro} = (1-S_w^*)^2[1-(S_w^*)^{\frac{2+\tau}{\tau}}] \tag{2}$$

$$S_w^* = [(S_w - S_{wir})/(1 - S_{or} - S_{wir})];\ P_c(S_w) = P_{ce}(S_w^*)^{\frac{-1}{\tau}};\ S_w + S_o = 1 \tag{3}$$

$$u_w = -\frac{kk_{rw}}{\mu_w}(\nabla P_w - \rho_w g \nabla Z) \tag{4}$$

The initial condition (IC) of P_w distribution within the rock sample is given in Eq. (5), which corresponds to the post-water flooding (or start of MEOR) process. In Eq. (5), u_w^0, k_{rw}^0, N_{ca}^0, and σ^0 are the values of u_w, relative permeability of water, Capillary number and IFT at the start of MEOR process. x and y are the direction along and across the flow. l_x and l_y are the length of the rock sample along x and y direction respectively.

$$u_{w,x}^0 = \frac{N_{ca}^0 \sigma^0}{\mu_w};\ P_w(x, y, t = 0) = \left\{ \begin{array}{l} P_{w,l};\ @(x = 0),\ y \\ \frac{\partial P_w}{\partial x} = -\frac{u_{w,x}^0 \mu_w}{kk_{rw}^0};\ @(0 < x < l_x),\ y \\ \frac{\partial P_w}{\partial x} = 0;\ (@x = l_x),\ y \end{array} \right\} \tag{5}$$

The value of P_w at the inlet boundary condition (BC) and outlet BC is given by Eq. (6)

$$\text{At inlet},\ \left(\frac{\partial P_w}{\partial x}\right)_{x=0,y,z,t} = -\left(\frac{Q_n}{A_r}\right)\left(\frac{\mu_w}{kk_{rw}}\right);\ \text{at outlet},\ \nabla p_w = 0 \tag{6}$$