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The effect of pore morphology on microbial enhanced oil recovery

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ABSTRACT

The microbial enhanced oil recovery mechanisms of bioclogging and interfacial tension reduction are evaluated for a range of pore morphologies to elucidate pore morphological effects on residual oil blob mobilization. The tested pore morphologies are the following; glass beads, angular crushed glass, and Bentheimer sandstone. x-ray computed microtomography (CMT) was utilized to characterize the pore morphologies and analyze residual oil blob mobilization during MEOR. Results demonstrate that bioclogging with interfacial tension reduction is the most effective MEOR treatment option in terms of additional oil recovered (AOR) for the pore morphologies with the smallest pore throat radii and that AOR increases with increasing pore body and throat radii, as well as pore sphericity. Other parameters analyzed, including porosity, coordination number, and aspect ratio displayed no correlation with AOR. In the more angular pore morphologies, collected CMT images illustrated that break-up (i.e. large oil ganglia breaking into smaller residual oil droplets) occurred during microbial treatment. Additionally, oil recovery was found to increase with the amount of biomass infused.

1. Introduction

Microbial enhanced oil recovery (MEOR) involves the inoculation of an oil reservoir with exogenous microorganisms or augmentation of the native microbial population to facilitate the mobilization of residual oil. For an in-depth review of MEOR and the mechanisms involved, we refer to Youssef et al. (2009). Overall, in terms of oil recovery, lab-scale experiments have been mostly successful (e.g. Armstrong and Wildenschild, 2012a, 2012b; Bordoloi and Konwar, 2008; Bryant et al., 1990; Suthar et al., 2009) while field-scale results are variable (e.g. Hiltzman, 1988, 1983; Lazar, 1991). Deleterious microbial activity or counterproductive effects due to the combination of multiple incompatible MEOR mechanisms (as discussed later) are potential reasons for inconsistent field-scale success. In this report, we investigate the MEOR mechanism of interfacial tension reduction with and without the MEOR mechanism of bioclogging, in various pore morphologies, to understand the synergistic/antagonistic relationship between these two MEOR mechanisms and ultimately how this relationship affects oil recovery.

Either beneficial or detrimental microbial activity is possible (Bao et al., 2009) during MEOR. Beneficial microbial activities include; biosurfactant production which reduces interfacial tension (e.g. Bryant and Douglas, 1988; Armstrong and Wildenschild, 2012a, 2012b), generation of biogenic gas which can dissolve into the oil phase and reduce its viscosity (e.g. Bryant and Burchfield, 1989), or hydrocarbon degradation which can reduce oil viscosity by microbial conversion of long chain alkanes to shorter chain alkanes (e.g. Wankui et al., 2006). Detrimental microbial activities include; generation of hydrogen sulfide which is highly corrosive to oil-extraction equipment (e.g. McInerney et al., 1991) or bioclogging which can potentially inhibit oil blob mobilization (Soudmand-asli et al., 2007). While many researchers report on the synergistic effects of linking multiple MEOR mechanisms, it is also likely that counterproductive effects occur.

Herein, we investigate the MEOR mechanism of IFT reduction with and without the MEOR mechanism of bioclogging since previous studies (Armstrong and Wildenschild, 2012a) indicate that in 3-dimensional columns packed with glass beads, both treatment options produced similar results. Whereas, conversely, in 2-dimensional micromodel experiments (Armstrong and Wildenschild, 2012b) bioclogging with IFT reduction significantly enhanced oil recovery in comparison to oil recovery with just IFT reduction. In both of these studies it was shown from CMT images that the oil/water interface increased in water-wet curvature after treatment with JF-2 and thus wettability alteration is rather unique to the bacterium used. In contrast to these results, Soudmand-asli et al. (2007) demonstrated that bioclogging may

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inhibit oil recovery in fractured 2-dimensional micromodel networks. Thus, it is likely that oil recovery via MEOR is governed, to a high degree, by pore morphology. It is our proposition that depending on pore morphology, IFT reduction combined with bioclogging could be either detrimental or beneficial to oil recovery. Thus, the goal of this research was to determine the most advantageous MEOR mechanism (i.e. IFT reduction versus IFT reduction with bioclogging) for different pore morphologies, in terms of measureable pore-scale morphological parameters that can be resolved using x-ray computed microtomography (CMT) images of porous media.

To facilitate this research we utilized the software package 3DMA-ROCK, which analyzes segmented CMT images of porous media and divides the pore-space into individual pore bodies separated by pore throats (Lindquist, 2002). 3DMA-ROCK has been utilized by numerous researchers to characterize porous media and study multiphase flow (e.g. Joekar-Niasar, 2010; Al-Raoush and Willson, 2005; Prodanović et al., 2007), understand changes in pore morphology during biomineralization (Armstrong and Ajo-Franklin et al., 2011), and dissolution processes (Cai et al., 2009). Pore morphology quantification is accomplished by constructing a medial axis through the void space (i.e. pore-space), followed by searching the medial axis for regions of minimal surface cross-sectional area, which are then defined as throats. 3DMA-ROCK divides the pore-space into individual pore bodies separated by throats, which represent only a surface and have no volume. Network characterizing parameters such as pore radii, throat radii, coordination number, and pore aspect ratio, are obtainable.

Numerous reports confirm that oil blob morphology and oil saturation, which ultimately affect oil blob mobilization and thus MEOR, are directly dependent on pore morphology (Schnaar and Brusseau, 2005, 2006; Costanza-Robinson et al., 2008; Brusseau et al., 2009). Results from these studies demonstrate that residual oil blob size distributions, interfacial area, and residual oil area-to-volume ratios, as well as the skew of these distributions, are directly related to morphological characteristics such as mean grain size, grain surface area, grain size homogeneity, and angularity. Furthermore, the inclusion of pore-scale parameters and realistic porous networks/domains into numerical models have lead to accurate prediction of various multiphase flow properties of relevance to oil recovery (e.g. Karpyn and Piri, 2007a, 2007b; Porter et al., 2010; Joekar-Niasar et al., 2010).

Successful implementation of MEOR also requires an understanding of, and the ability to control, reservoir microbiology. Often, reservoir treatment schemes are designed to augment reservoir specific microorganisms, and thus, control which MEOR mechanism is utilized for recovery. For example, the addition of nitrate, nitrite, or nitrate/molybdate mixtures have been used to inhibit the activity of sulfate reducing bacteria (Youssef et al., 2009; Bao et al., 2009; Jackson et al., 2010). Bao et al. (2009) conducted selective activation experiments on formation water from the Shengli oilfield in China and successfully stimulated the growth of hydrocarbon degrading bacteria and methane producing bacteria, while simultaneously restricting the growth of sulfate reducing bacteria. Field-scale reservoir characterization is often accomplished using DNA microarrays (Jackson et al., 2010), which target highly conserved species-specific regions of an organisms 16s rRNA. Zhang et al. (2010) used 16s rRNA characterization to study microbial community response during the injection of bacteria and nutrients into the Daqing oilfield in China. In their complementary laboratory experiments, Zhang et al. (2010) found that the targeted bacteria were easily activated; however, at the field-scale the targeted bacteria did not survive and the activated microbial communities were not the ones predicted based on the lab-scale experiments. Field trials, such as these, demonstrate that shifts in species specific population densities are likely to occur during MEOR. While further advances are needed to better control/characterize subsurface microbial communities, knowing which MEOR mechanism is the most advantageous for a given reservoir, in terms of physical reservoir parameters, will help optimize future MEOR efforts.

2. Materials and methods

2.1. Pore morphologies

Different diameter glass spheres and/or crushed glass were packed into columns ((I.D. = 6 mm, length = 60 mm) and sintered in a muffle furnace at 760 °C for 20 min. In total 4 artificial pore morphologies were constructed:

(a) Graded spherical mixture
  - 35%, 600 μm diameter glass spheres
  - 35%, 850 μm diameter glass spheres
  - 30%, 1.0 to 1.4 mm diameter glass spheres

(b) Poorly graded spherical mixture
  - 50%, 400 μm diameter glass spheres
  - 50%, 1.0 to 1.4 mm diameter glass spheres.

(c) Fine angular mixture
  - 100%, crushed glass $<$ 800 μm (nominal sieve opening)

(d) Fine/coarse angular mixture
  - 50%, crushed glass $<$ 800 μm (nominal sieve opening)
  - 50%, crushed glass $>$ 800 μm (nominal sieve opening)

For the graded spherical mixture the glass spheres were well-mixed during column packing, the opposite was the case for the poorly graded spherical mixture. The fifth tested pore morphology consisted of consolidated Bentheimer sandstone cores which were wrapped in Teflon tape and sealed with epoxy inside the same diameter glass columns as the artificial morphologies.

2.2. MEOR

Columns were sterilized with 3 pore volumes of ethanol and then rinsed with 3 pore volumes of Media E as used in Armstrong and Wildenschild (2012a, 2012b), (Table 1). Columns were then saturated with Soltrol 220 followed by water flooding with Media E. Water flooding was performed under fixed flux conditions at 0.18 mL/h with a precision syringe pump. Once 3 pore volumes of Media E had been pumped through, it was assumed that residual oil saturation was established, and at this point, the column was imaged. MEOR treatment commenced after water flooding by infusing a given MEOR flooding solution (as described below) at 0.18 mL/h and the columns were periodically imaged. For JF-2 treatment once the columns were imaged the test was terminated since x-rays kill the bacterium. Therefore, multiple independent column experiments were conducted for different extended periods of time to provide temporal oil recovery data.

Table 1
Brine-based growth media called Media E, used for water flooding and MEOR.

Media E	
NaCl	25 g/L
$(NH_4)_2SO_4$	1 g/L
$MgSO_4$	0.25 g/L
Glucose	10 g/L
Phosphate buffer	100 mM
Trace metals solution	1.0%
Yeast extract	2.0 g/L