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# Experimental and Numerical Study of Microbial Improved Oil Recovery in a Pore Scale Model by using COMSOl

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**Abstract:** A number of visualization experiments are carried out at the laboratory temperature with dodecane and an alkane oxidizing bacterium, *Rhodococcus* sp 094, suspended in brine for evaluating the performance of microbial improved oil recovery (MIOR) in a glass micromodel. The observations show the effects of bacteria on remaining oil saturation. The interfacial tension reduction, wettability alteration and flow pattern changes are recognized as active mechanisms. COMSOL Multiphysics 4.2 is used to simulate the two phases flow obtained experimentally at the pore scale within the micromodel. The model attempts to account for the interactions between these acting mechanisms. The impact of the interfacial tension reduction and wettability alteration on the flow pattern are presented and discussed. Consequently, displacement mechanisms of oil phase by water phase containing bacteria are investigated based on analysis of experimental results and numerical modeling of the MIOR process. Based on numerical results, COMSOL Multiphysics 4.2 will have a potential to be a valuable tool for numerically simulating the MIOR process at the micro scale.

**Keywords:** Reservoir engineering, Pore scale model, MIOR Process, Glass micromodel, IFT, wettability, biomass, Bacteria suspension.

## 1. Introduction

A Microbial Improved Oil Recovery (MIOR) method is introduced as the potential method in addition to other EOR methods. The MIOR method is the use of microorganisms and their metabolic activities. Residual oil is trapped after implying waterflooding. The MIOR process helps mobilizing the residual oil saturation and thereby increases the reservoir recovery. The potential recovery mechanisms involved in MIOR processes include interfacial tension reduction, wettability alteration, selective plugging, gas generation, acid production and mobility ratio reduction. Although many laboratory experiments and field applications have investigated the effect of bacteria on increasing oil recovery after water flooding (Bryant et al. 1989, Sunde et al. 1992, Sayyouh et al. 2002, Maudgalya et al. 2007, and Town et al. 2010), but there are few studies on pore network modeling. Pore scale models are powerful tools principally for modeling processes and phenomena involved in microbial flood in porous media. These models may capture realistic features of MIOR processes and lead to a better understanding of the recovery mechanism (Khan et al. 2008, Raeesi and Piri, 2009 and Joekar-Niasar et al. 2010).

A number of experiments have been carried out at the laboratory condition to evaluate the MIOR process within the glass micromodel, and the interfacial tension reduction, changes in wettability and flow pattern are proposed as the driving mechanisms contributing to increased oil recovery. Bacteria can produce surface active components (surfactants) that are capable to reduce the interfacial tension, to alter the wettability of the reservoir, and to plug the high permeability pore channels in the reservoir rock. As the bacteria have access to nutrients, a carbon source and oxygen and favorable environmental conditions, they can activate one or more of these mechanisms.

Therefore, this paper presents numerical results of the MIOR process based on the experiments. COMSOL Multiphysics 4.2 is used to simulate the two phases flow at the pore scale within the micromodel.

## 2. Experiment

A number of flow visualization experiments have been implemented to get better insight mechanisms in the two phases flow with bacteria within a pore scale medium. Dodecane (as oil phase), synthetic brine and an alkane oxidizing bacterium, *Rhodococcus* sp 094 suspended in brine (as water phase) and micromodels (as porous media) have been employed. The densities of brine, bacteria suspension and dodecane are 1.03, 1.02 and 0.75 g/cm$^3$ respectively. The viscosities are 1.04, 0.98 and 1.47 cp for the brine, bacteria suspension and dodecane. The details of the experiment have been earlier published by Shabani Afrapoli et al (2011). The experimental pore network pattern is shown in

**Figure 1**. The pore structure consists of pores and pore throats with various sizes. The average depth of etched flow channels is about 100µm. The pore channels have a width ranging from 350 to 570µm. The diameters of small, medium and large grains are about 400, 900 and 1450µm, respectively.

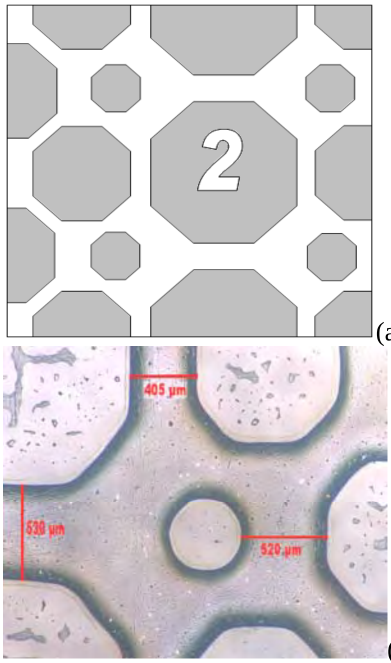


**Figure 1:** Experimental pore network (a) designed, (b) etched on the glass.

To conduct the experiment, the micromodel is saturated with displaced fluid (oil). The displacing fluid (brine or bacteria suspension) is pumped from the reservoir and through the flow line it is injected into the micromodel. The fluid flow is recorded by monitoring the system and the fluid volume is collected in a graduated tube.

**Figure 2** shows the distribution of oil saturation during floodings. Observations show effects of bacteria on remaining oil saturation. The dashed circle area is selected to evaluate how the remaining oil is changed. The water flooding has implemented to displace the oil out of the medium in order to achieve residual oil saturation ($S_{or}$) as shown in **Figure 2-a**. The residual oil is reduced as the flooding is continued with bacteria. The lowered residual oil saturation is shown in **Figure 2-b, c**. This is due to the interfacial tension reduction and wettability changes. The bacterial mass grows at the fluid interfaces and pore wall as shown in **Figure 2-d**. Consequently the biomass plugs the pore channels and changes the flow pattern.

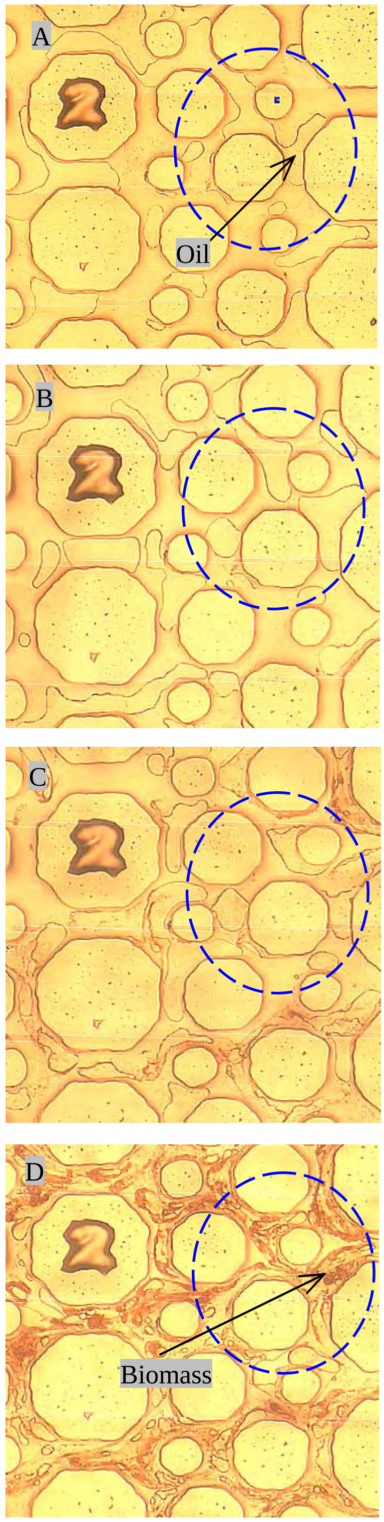


**Figure 2:** Residual oil saturation after (a) water flooding (b) 2 days of bacterial flooding (c) 4 days and (d) 6 days- biomass.

## 3. Simulation

The two phases flow is modeled by using COMSOL Multiphysics 4.2. The main goal is to study the oil displacement process by the simulator.

### 3.1 Model Description

A 2D pore network is constructed based on images of small regions of a glass micromodel. The dimension of the simplified model as shown in **Figure 3** is 8.5mm x 8.5mm. The length unit used in models is micron, so the size for every grain is the same grain size etched on the glass micromodel. The right side is an outlet and left side is an inlet, upper and lower edges are closed boundary.

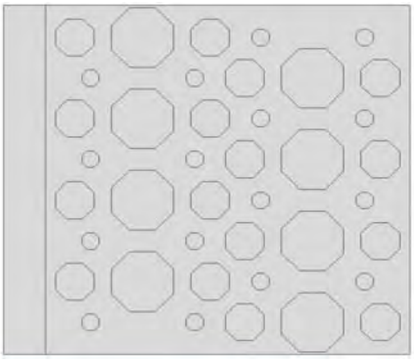

**Figure 3:** Simplified 2D model

### 3.2 Base Case Model

The base case model is the model with initial parameters used for experiments. The grain and pore arrangement of the model is exact identical to the experimental pattern. The similar properties of water and oil used for experiments are used in simulation. The initial saturation distribution of oil (red) and water (blue) is shown in **Figure 4**.

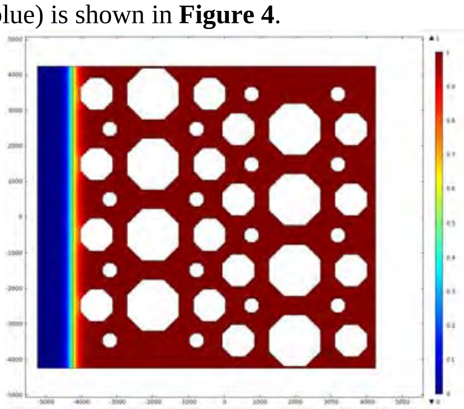

**Figure 4:** Initial saturation distribution of oil (red) and water (blue)

The spontaneous water imbibition process occurs in the water wet model without any injection pressure. So that, the initial oil wet model is selected to simulate the MIOR process. The inlet side is controlled by the injection pressure and the outlet pressure is zero. However, water is injected from the inlet side and oil is produced from the outlet side.

### 3.3 Simulation Models

Three cases are modeled for simulation study of water and bacterial flooding process in the 2D model. The description of each model is as follows.

Case 1: Threshold and Injection Pressure Model – Six simulations with different injection pressures are conducted to obtain the threshold pressure and optimal injection pressure required for the water flooding process.

Case 2: Interfacial Tension (IFT) Model – Experimental results show that the IFT between oil and water is 0.0183 N/m. The IFT is experimentally reduced to 0.005 N/m between oil and the bacteria suspension. Therefore, two runs are performed with the IFT's of 0.0183 N/m and 0.005 N/m to evaluate the effect of IFT on the oil displacement process

Case 3: Wettability Alteration Model –The experiments show that the initial oil wet model has a contact angle of 125$^{o}$. When the system is exposed to the bacteria suspension, the contact angle is changed to the less oil wet state where the contact angle is 117$^{o}$. The neutral wet (90°) and water wet (30°) models are introduced to compare results with other wettability states. Totally, three runs are done for evaluating the effect of wettability status on the oil displacement.

## 4. Results and Discussions

The experiments and simulations of two phase flow in the pore scale model have been performed to specify how the oil is displaced by water or bacteria suspension in the MIOR flooding process. The result of experiments has been already published elsewhere by the authors. Therefore, in this article, the most focus is given to the results from the simulation part. The simulation results are compared with the experimental results. Effects of driving mechanisms on the oil displacement process are evaluated in the following.

### 4.1 Effect of Threshold Pressure on Oil Displacement

In the base case model, water is displacing the oil. The wettability of model is oil wet. The 2D model has different pore channel sizes. The threshold pressure has to be determined to simulate the fluid flow in the whole model. Different simulation cases with injection pressure ranging from 20Pa, 30Pa to 70Pa for one second are run to determine the threshold pressure. All cases are reached the steady state at the end simulation. The results show that if the injection pressure is less than 30Pa, water can not flow through the pore channels due to the high capillary force resistance. As the injection pressure is increased to 40Pa and 50Pa, water can flow through the pore channels, but these pressures are still not sufficient to overcome the capillary force in narrow throats. However, as the injection pressure rises to 70Pa, the water breakthrough happens as shown in **Figure 5**.

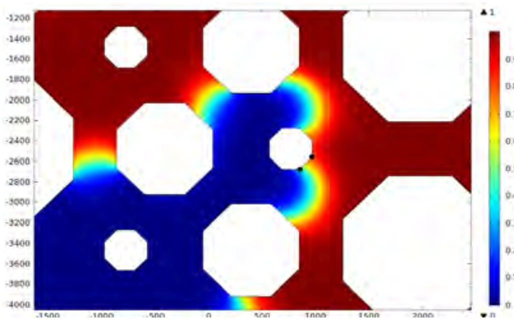

**Figure 5:** Partial saturation distribution at 0.1 second for 70Pa injection pressure

Two points are selected where one in oil phase (red) and another in water phase (blue), the pressure difference between two points is the approximate value for threshold pressure. For instance, the pressure difference for two points (**Figure 5**) at 0.1 second is about 53Pa where the injection pressure is 70Pa. Water can breakthrough the simplified model over 70Pa injection pressure, but this simulation model has poor sweep efficiency due to oil wet wall of model and relative high capillary pressure for some small pore channels. Therefore, the approximate injection pressure is determined to have relative good sweep efficiency. Different simulation cases with inlet pressure varying from 80Pa to 150Pa are run. The distributions of oil and water saturation at end of simulation for 80Pa, 90Pa, 100Pa and 150Pa injection pressure cases are evaluated to determine an optimal injection pressure. However, the evaluation result shows that the oil recovery of 80Pa injection pressure case is lower than that of 90Pa injection pressure cases, while when injection pressure is greater than 90Pa oil recovery does not increase too much and keeps almost constant. The breakthrough time for a case where the injection pressure is more than 90Pa is too early, so 90Pa is selected as the injection pressure for following simulation study.

### 4.2 Effect of IFT Reduction on Oil Displacement

**Figure 6** and **Figure 7** show the simulation results regarding the effect of the interfacial tension on the oil displacement. The interfacial tension between oil and water is 0.0183N/m. The result of saturation distribution at 0.15 second is shown in **Figure 6**. As observed from the figure, some oil has remained in the model after the water flooding. This is due to the high interfacial tension between oil and water and shows there are parts where are not swept well. This is a good agreement with the experimental results.

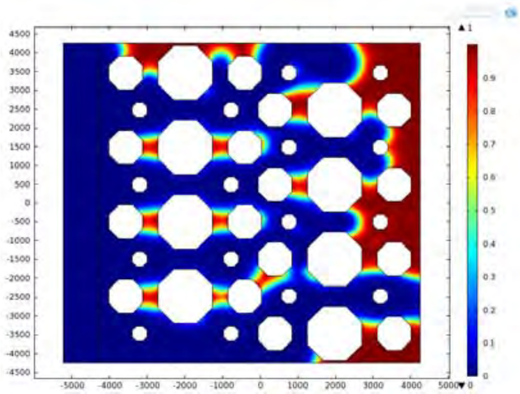

**Figure 6:** Saturation distribution of oil and water at 0.15 second for IFT: 0.0183N/m (Base case)

The residual oil saturation decrease significantly with a low interfacial tension. Lowering the interfacial tension is one of the main tasks in enhanced oil recovery methods. The interfacial tension is reduced by using chemicals, surfactants and bioproduct. The authors have previously measured the low interfacial tension between oil and bacteria suspension. As the bacteria suspension is used instead of brine, the interfacial tension of 0.005N/m is obtained. **Figure 7** shows the saturation distribution of oil and bacteria suspension with the low interfacial tension, 0.005N/m. The result shows that the reduction of interfacial tension has strongly effects on oil recovery, by improving sweep efficiency. As the interfacial tension is lowered, the friction force between oil and water phase and also capillary pressure are reduced. As observed in **Figure 7**, the oil saturation of unswept areas (indicated as red color in **Figure 6**) has changed to lower residual oil.

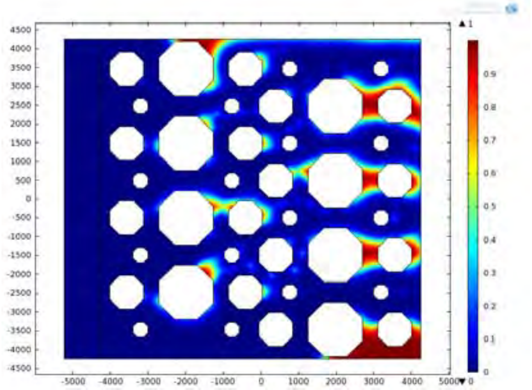

**Figure 7:** Saturation distribution of oil and water at 0.15 second for IFT: 0.005N/m

### 4.3 Effect of Wettability Alteration on Oil Displacement

Wettability of the reservoir rock is an important parameter to characterize the oil displacement process. Changes in wettability result in the saturation profile in porous media. In the MIOR process, bio-products can change the wettability of the grains. Shabani Afrapoli et al. (2009) have measured the wettability alteration during core floodings between oil and bacteria suspension. Different simulation models with different wettabilities are conducted to investigate the effect of wettability alteration. Changes in the oil saturation distribution are compared with the oil saturation distribution observed in the **Figure 6**. The contact angle in the base case has changed to 117° as the bacteria suspension is used. The simulation result for this case is shown in **Figure 8**. The result shows that when the wettability of grains is less oil wet, the profile of residual oil saturation distribution is modified. It indicates that the residual oil has reduced. This result is consistent with the experimental results, previously reported by Shabani Afrapoli et al. (2011).

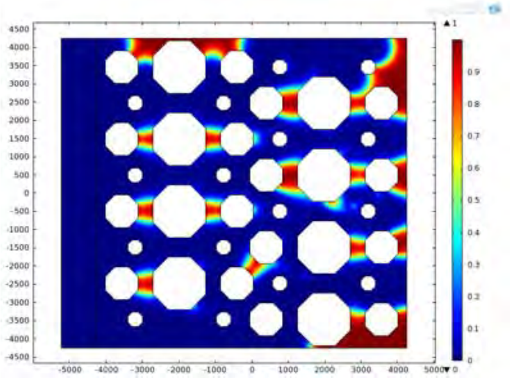

**Figure 8:** Oil saturation distribution at 0.15 second for the contact angle θ = 117°

Although the experiments show that the bacteria have changed the wettability state of grains from oil wet to less oil wet, but it is still in the oil wet region. There are three types of wettability modes. Water wet is the state where the contact angle is less than 45°. For the neutral wet, the contact angle is 90° and for the oil wet state, the contact angle is higher than 90°. However, two simulation models are conducted with the neutral wet and water wet properties to compare the result with neutral and water wet states. The simulation result of the neutral wet state is shown in **Figure 9**. The result shows that more oil is produced as the wettability has changed to the neutral wet state.

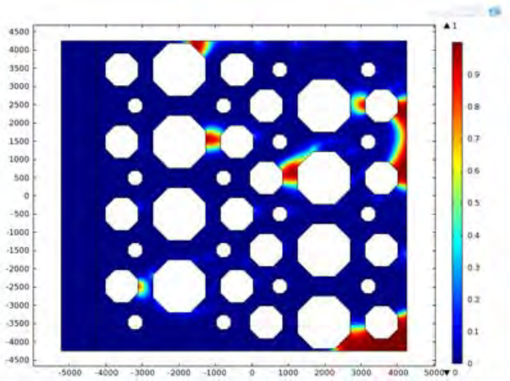

**Figure 9:** Oil saturation distribution at 0.15 second for the contact angle θ = 90°

**Figure 10** shows the simulation result of the water wet model. The water is imbibed into the model spontaneously and the residual oil saturation is decreased significantly. The simulation result shows that oil recovery is increased significantly in the water wet model. This result is very optimistic in the real reservoir. In the reservoir, there are different pore channels rather than pore throats used in the 2D simplified model.

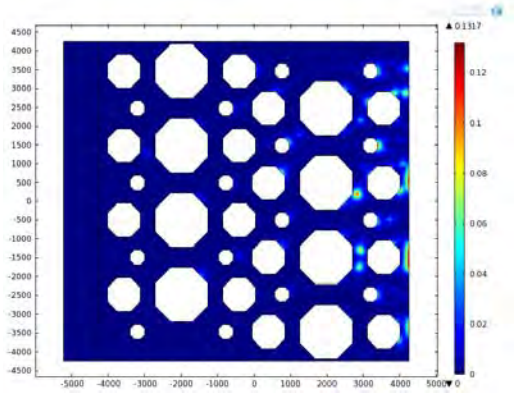


**Figure 10:** Oil saturation distribution at 0.15 second for the contact angle θ = 30°

Therefore, the capillary pressure especially in narrow pore throats is high and does not allow the recovery of oil increases significantly.

## 5. Conclusions

COMSOL Multiphysics 4.2 is introduced as the new simulator to model the oil displacement process at pore scale. The 2D simplified model is built based on the micromodel. The injection pressure of 90Pa is determined for simulating the flooding process. The interfacial tension reduction, wettability changes and pore blocking are experimentally proposed as driving recovery mechanisms for the MIOR process. The effects of interfacial tension reduction and wettability alteration on the oil displacement process are studied by the COMSOL simulator. The selecting pore plugging process is more complicated, so it is not studied by the simulator. The simulation results are compared with the experimental results. Consequently, the COMSOL simulator has a potential to solve the simulation problems of the displacement process at the pore scale. Especially for the MIOR process, it is used to model the effect of interfacial tension reduction, wettability alteration on oil recovery.

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## 7. Acknowledgements


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