MICROBIAL ENHANCED OIL RECOVERY - MECHANISM

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ABSTRACT

It is well known from several core scale experiments that microbial activity inside a core may lead to enhanced oil production. In this work we argue that the only realistic microbial mechanism that contributes to oil production is that of the biofilm type, simply because of the low concentration of microbes inside the porous media. Microbial activity can lead to formation of a biofilm on the rock surface and the oil water interface. By modelling the microbes as immiscible drops we show that they can change the wetting properties of the rock. The model used is a Lattice Boltzmann algorithm for solving the multiphase Navier-Stokes equations. Experiments with two strains of microbes from oil fields have been performed. The experiments are focused on studying the ability of microbes to attach to interfaces and surfaces and thereby change the wetting properties of oil, brine and rock. The first type is a microbial capillary tube experiment where microbes grown inside capillary tubes may change the interfacial or wetting properties of the tubes. A change in interfacial tension or wetting characteristic can be observed as a change in height of the oil water interface. The second type is a sessile drop experiment, where the contact angle of an oil drop has been observed over time, while subjected to microbial activity.

INTRODUCTION

Microbial enhanced oil recovery (MEOR) is motivated by the fact that numerous core scale experiments have shown an increased oil production due to microbial activity. In some cases the increased oil production has been extremely high while in some cases very low (see Bryant and Lockhart (2000)). The experimental evidences are convincing that something is going on inside the core which increases the oil production. The interpretation of core scale experiments is complicated due to one simple reason that when oil is released, one never really knows what kind of mechanism is responsible for the increased oil production. Even if the microbes or product produced by the microbes was responsible for the extra oil produced, one does not know precisely what they did. The core acts as a black box. In order to do a field trial or pilot one needs to understand in detail what the microbes are doing. As an example core scale experiments are often performed on water wet cores. If the mechanism for extra oil production is wettability

change towards more oil wet behaviour, then one needs to take into account that the reservoir is probably not water wet, but mixed wet.

MEOR MECHANISM - GENERAL CONSIDERATIONS

In Table 1 a list of the different possible mechanism for EOR due to microbial activity is shown. In order for the products on the left side in Table 1 to have the effect listed on the right hand side, these substances must be produced at a sufficient amount.

Polymers, Surfactants and Acid

Experience with polymer, surfactant and acid stimulation indicates that the required concentration is about $C_{surfactant,acid} \sim 10^{-2}$ kg/kg water and $C_{polymer} \sim 10^{-3}$ kg/kg water for attaining improved oil recovery(Green and Willhite (1998)). The surfactant concentration needs to be this high to cover the adsorption in the porous media. The crucial question is then how much polymer or surfactant can be produced by the microbes. The answer to this question clearly depends on the concentration of the microbes present in the reservoir. Typical microbial concentration in lab experiments range from 10^5-10^9 microbes/ml. In the reservoir where the growth conditions are not optimal and a limited amount of nutrients is available the concentration will probably be closer to 10^6 cells/ml. The microbes have a density similar to water and the typical radius is r_b=1 μm, hence the mass of a spherical microbe is $m_b = 4/3\pi\, r_b^3 \rho_w = 4 \cdot 10^{-12}\, g$. Assuming that the microbes can produce an amount of a chemical agent equivalent to their own mass, then the concentration of the chemical is:

$$C = \left(10^5 - 10^9\right) m_b / ml \approx \left(10^{-6} - 10^{-2}\right) \text{kg/kg water} \qquad (1)$$

The result from this calculation compares well with Yakimov et al. (1997). In that paper the maximal concentration of microbes was $5 \cdot 10^8$ cells/ml and the maximal concentration polymer and surfactant was (0.2-1.5) g/l and (0.05-0.15) g/l respectively. Assuming a concentration in the reservoir of about 10^6 microbes/ml would then give 10^{-5} kg/kg water. This is at least two orders of magnitude smaller than the concentration needed for an EOR effect, hence it is very unlikely that a high enough concentration for surfactant or polymer can be reached in a real field situation.

Gas Production

The obvious choices for gas production are methane due to microbial activity, CH_4, and carbon dioxide, CO_2. Assuming methane and carbon dioxide to behave as an ideal gas with an ideal gas constant of R_{CH4}=518.3 J/kg K and R_{CO2}=189.9 J/kg K, we can estimate the saturation of gas in a reference volume V_{ref}.

$$S_g = \frac{V_g}{V_{ref}} = \frac{m R T}{p V_{ref}} = C \frac{RT}{p} \qquad (2)$$

C is the mass concentration of the microbes in the reference volume. Assuming T=60^0C, p=100 bar, we find $S_g \sim 2 \cdot 10^{-4}$ (CH_4) and $S_g \sim 6 \cdot 10^{-5}$ (CO_2). (Some of these gases might be

dissolved in the fluid and rock). Clearly, a very long time must pass in order for a sufficiently large volume of gas to be produced.

Biofilm

Biofilms can grow on the surface of the porous rock, which may lead to a change of surface properties and/or a decrease in permeability (Gandler et al. (2006)). Permeability reduction can not explain increased oil production from water wet cores. The properties of the biofilm will be different from the rock properties. The change in surface properties inside the porous rock can thus lead to a change in the wetting properties. If the microbes locally change the wettability close to a trapped oil cluster, this oil cluster can be mobilized when the receeding contact angle is reduced sufficiently. In addition microbes attached to the oil water interface will not detach easily (we will return to this point). Microbes would then be transported with the oil cluster to a new location and may induce new oil mobilization.

MICROSCALE MODEL FOR MICROBIAL INTERACTIONS

As stated earlier the typical size of a microbe is about one micron; this is the same order of magnitude as the pores and pore throats in a porous rock. Hence, the microbes must be modelled as cells and not a concentration on the pore scale. A very simple model for a bacterial cell is a vesicle. If one neglects the lipid bilayer of the vesicle one get an object very close to an immiscible drop. Hence, we assume that the microbes can be modelled as immiscible drops. A similar approach has also been used by Dupin et al. (2006), in their study of the flow of blood cells.

Lattice Boltzmann – BGK Algorithm for Microbial Cells

By making the simplification that the microbes behave as immiscible drops, we need a simulator that solves the Navier Stokes multiphase equations inside the pore space. We choose a Lattice Boltzmann (LB) algorithm (Succi (2001)). The appealing part of the LB approach is that it has an easy physical interpretation. The degrees of freedoms in a LB approach can be thought of as fictitious particles moving on a regular lattice. Particles meeting at a lattice point obey a collision rule. If there are multiple phases the neighbouring lattice points also contribute to the collision operator (Shan and Chen (1993)). As the particle picture is kept in a LB approach the introduction of forces and treatment of complex boundary conditions is straight forward. The continuum equations, such as the Navier-Stokes equations, have to be derived through a Chapman-Enskog expansion. Our intentions are to study the effect of immiscible drops attached to surfaces and interfaces. We will use exactly the same model as Hou et al (1995), a two dimensional nine speed model. More phases are introduced in the way described by Shan and Chen (1993). Each phase, *a*, obeys the following equation:

$$f_i^a(\mathbf{x}+\mathbf{e}_i, t+1) - f_i^a(\mathbf{x},t) = \frac{1}{\tau}\left[f_i^a(\mathbf{x},t) - f_i^{a(eq)}(\mathbf{x},t)\right], \qquad (3)$$

Where the equilibrium distribution function, $f_i^{a(eq)}$, is given by:

$$
\begin{aligned}
f_0^{a(eq)} &= \rho^a\left(1-\frac{3}{2}\mathbf{u}_a{}^2\right) \\
f_i^{a(eq)} &= \rho^a\left(1+3\left(\mathbf{e_i}\cdot\mathbf{u}_a\right)+\frac{9}{2}\left(\mathbf{e_i}\cdot\mathbf{u}_a\right)^2-\frac{3}{2}\mathbf{u}_a{}^2\right), i=1,2,3,4 \\
f_i^{a(eq)} &= \rho^a\left(1+3\left(\mathbf{e_i}\cdot\mathbf{u}_a\right)^2+\frac{9}{2}\left(\mathbf{e_i}-\mathbf{u}_a\right)^2-\frac{3}{2}\mathbf{u}_a{}^2\right), i=5,6,7,8
\end{aligned}
\tag{4}
$$

$f_i^a(\mathbf{x},t)$ represents the distribution of particles entering site **x** at time t and moving in direction *i* with velocity $\mathbf{e}_i$. The fluid velocity $\mathbf{u}_a$ and density ρ_a are determined by mass and momentum conservation:

$$
\begin{aligned}
\sum_i f_i^{a(eq)} &= \sum_i f^a{}_i = \rho^a \\
\sum_i f^{a(eq)} e_i &= \sum_i f^a{}_i e_i = \rho^a u^a{}_i
\end{aligned}
\tag{5}
$$

Fluid separation is obtained by a pseudo potential method, where the force between dissimilar particles is:

$$
\mathbf{F}^a(\mathbf{x},t) = -\sum_{a'} G_{a,a'}\psi_a(\mathbf{x},t)\sum_{i=0}^{8}\psi_{a'}(\mathbf{x}+\mathbf{e}_i)\mathbf{e}_i
\tag{6}
$$

The sum goes over all fluid phases a and the potential ψ_a is given by:

$$
\begin{aligned}
\psi_a(\mathbf{x}) &= \rho^a(\mathbf{x}) \\
G_{a,a'} &= \begin{cases} 0 & |\mathbf{x}-\mathbf{x}'| > \mathbf{e}_i \\ g_{a,a'} & |\mathbf{x}-\mathbf{x}'| < \mathbf{e}_i \end{cases}
\end{aligned}
\tag{7}
$$

The only parameter to play with then is $g_{a,a'}$, that is how much the different phases repel each other or how much attracted they are to the walls. The fluid separation force is incorporated as a shift in the fluid velocity:

$$
\rho^a(\mathbf{x},t)\mathbf{u}^a(\mathbf{x}) \rightarrow \rho^a(\mathbf{x},t)\mathbf{u}^a(\mathbf{x}) + \tau^a\mathbf{F}^a(\mathbf{x})
\tag{8}
$$

Microbial Capillary Effect

A very simple situation in which one can use the LB simulator is to study the effect of microbes (drops) on interfaces is the case with a capillary tube. Consider a capillary tube immersed in water and oil on top (see left figure in Figure 1). If the tube is water wet, water will imbibe into the capillary tube, with its height approximately described by the following equation:

$$h = \frac{2\sigma_{ow}\cos\theta_{ow}}{(\rho_w - \rho_o)\, g\, r}, \qquad (9)$$

where σ_{ow} is the interfacial tension between oil and water, ρ the density, g the acceleration of gravity, r the radius of the tube and θ_{ow} the oil water contact angle. In the right figure in Figure 1 results from the simulation are shown. After the imbibition process five "microbes" (drops) have been placed on the oil water interface. In one simulation, the drops were experiencing repulsion to the wall in the capillary tube and in another the drops felt an attraction to the wall. As is clearly seen from the figure, there is a decrease in the height of roughly 50% in the case of the drops adhering to the wall and a decrease of 10 % when the drops are not adhering. The decrease in height is a function of the parameters chosen in the simulation. If the microbes feel a stronger attraction to the wall the height would be more reduced. This effect has to be interpreted as a change in the wetting properties and can not be attributed to change in interfacial tension. To clarify this a bit more one can make a simple (analytical) calculation where one places a drop on the oil water interface in the middle of the tube. But we do not assume that the radius of curvature lies on the centre of the tube. From Figure 2, we find:

$$R\cos\theta_{ow} = l + R\sin\beta \qquad (10)$$

force balance and continuity of capillary pressure leads to :

$$\sigma_{23}\sin\beta + \sigma_{21}\sin\phi_1 = \sigma_{13}\sin\phi_2 \qquad (11)$$

$$\frac{\sigma_{23}}{R} = -\frac{\sigma_{21}}{R_1} + \frac{\sigma_{13}}{R_2} = \frac{1}{r}(-\sigma_{21}\sin\phi_1 + \sigma_{13}\sin\phi_2).$$

Combining the last two equations gives:

$$\frac{1}{R} = \frac{\sigma_{23}\sin\beta}{r} \qquad (12)$$

From equation (11) it then follows, that the curvature is

$$\frac{1}{R} = \frac{\cos\theta}{l + r}. \qquad (13)$$

Clearly l+r=D/2 and we find 1/R=2cosθ/D, this implies that the drop introduces no change in pressure across the curved surface. Or stated differently no change in interfacial tension should appear.

Some additional insight can also be gained by calculating the energy needed to *remove* a spherical particle from an oil water interface, the result is (Binks (2002)):

$$E = \pi r_b^2 \sigma_{ow} (1 \pm \cos\theta)^2. \qquad (14)$$

The plus sign is for removal into the oil phase. At 50^0C, σ_{ow}=50 mN/m and r_b=1 μm this energy is $E=35 \cdot 10^6$ k_BT (1-cosθ). The detachment energy is much larger than any energy associated with thermal motion. If particles (microbes) attach to interfaces, they are attached irreversibly. From equation (14) it follows that there is a strong dependence on wettability and the detachment energy has its maximum at $\theta_{ow}= 90^0$. If the microbes are completely water wet or oil wet, the detachment energy are zero and therefore they will not stay at oil water interfaces. Particles attached to oil water interfaces have been known for quite some time can stabilize emulsions (Binks (2002)).

To summarize:

1. A microbe on an oil water interface introduces *no change in interfacial tension.*
2. Microbes can prevent oil drops from coalescing by attaching to them.
3. If the microbes attach to the wall *and* the oil water interface a change in the apparent contact angle is to be expected.
4. In order for microbes to detach from an oil water interface, *energy* needs to be transferred. It does not happen spontaneously.
5. Wetting status of microbes should neither be completely oil wet or water wet in order for attachment to be possible.

A recent experimental publication actually proves the first two points (Dorobantu et al. (2004)). This strengthens the assumption that, with respect to modelling, microbes can be well represented as immiscible drops.

EXPERIMENTAL RESULTS

We strongly believe that the way to attack microbial mechanism with respect to EOR is simple experiments. In this context simple refers to easy-to-interpret. Core flooding experiments are time consuming and after the experiment there are always room for debate on what really went on inside the core. From the theoretical considerations in the previous section, the most promising mechanism is of the biofilm type. It needs low concentration and it is actually the only mechanism in Table 1 which is a pure microbial mechanism. That is, there have to be microbes present in the core in order to generate a biofilm. That the microbes themselves play a crucial role in the recovery of extra oil was nicely illustrated in the paper by Yakimov et al. (1997). In that paper they compared coreflooding with only the EOR products (polymer and surfactant) produced by the bacteria and coreflooding with microbes present. The conclusion was that the cores containing microbes had a much higher recovery. In the following we present results from two “pore scale” experiments. One is a capillary tube and the second is a contact angle experiment.

Capillary Tubes

The height in a vertical capillary tube is given by equation (9). We used four glass pipettes (water wet) (HIRSCHMANN), 1, 0.5, 0.2, 0.1 ml with radii 1.35, 0.94, 0.53, 0.44

and one polypropylene (oil wet) 1 ml with radii 1.43 mm. During a period of 14 days, the height decreased by approximately 50 %. We made three experiments (aerobic) with the strain *Bacillus Lichenformis*, also used by Yakimov et al (1997). The model was inoculated with 10 % inoculum of *Bacillus Lichenformis*. All three experiments showed an decrease in height in all the tubes of approximately 50 %, see Figure 3. The interfacial tension measured before and after was 14.5 mN/m and 6 mN/m.

Two experiment (anaerobic) was performed with microbes from a North Sea reservoir, these do not produce any surfactants as the strain *Bacillus Lichenformis* do. No change in interfacial tension is expected. We performed one experiment with a magnetic stirrer in the bottom of the model, which was turned on for 10 minutes every hour. In the model a change of height in the polystyrene tube was observed, the height in the glass tubes was more or less constant over time (see Figure 4). This indicates a change in wettability of the plastic tube from oilwet to neutral wet. We did a second run with no stirring and found no change in height over time.

Contact Angle Measurements

An aerobic container was made for contact angle measurements as drawn in Figure 5. In the middle of the container a horizontal plate was placed. The container where filled with microbes and medium. Several drops of n-decane where placed on the plate and the contact angle was measured. Three trials with glass plate, two trials with slices of carbonate and one with a steel plate, were performed. For the glass plates, steel plate and carbonate no change in contact angle due to microbial activity was observed over time. For the steel plate a change in contact angle was measured over time and a film was observed on the steel plate. Investigating the film on the steel plate by SEM imaging, no traces of microbes were seen.

CONCLUSIONS

We argue that the concentration of microbes in realistic cases would be too small to produce sufficient amount of polymer, acid and surfactants. Then the only realistic mechanism is that of the biofilm type. In order for microbes to mobilize trapped oil they only need to cover a small area, hence it is a low concentration mechanism. A physical based model of microbial interactions is presented. It has the ability to explain how microbes can stabilize emulsions; it also shows that microbes can change the wetting properties of the rock. By simple calculation we have shown that microbes attached to an oil water interface will stick to it. These microbes can be transported with oil drops in the porous media and start growing when oil drops stop flowing. The experiment show that some kind of flow in the system is of importance, the reason being that it helps microbes to attach to interfaces. Static contact angle measurements did not show any change in wetting properties. Results from the capillary tube experiment give some indications that the microbes can change the wettability. However, the experiments need to be confirmed by running more tests.

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NOMENCLATURE

σ_{12}	Interfacial tension between phase 1 and 2
θ_{12}	Contact angle between phase 1,2 and rock
ρ	Fluid density
g	Gravitational constant
r_b	Radius of microbe, typical $1\,\mu m$
C	Microbial concentration
k_B	Boltzmanns constant $1.380\ 10^{-23}$ J/K
T	Absolute temperature

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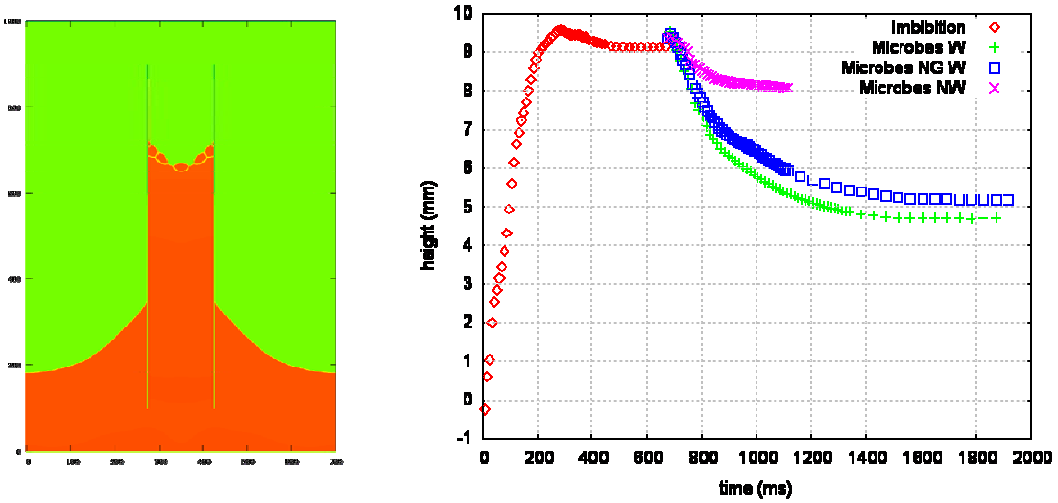

Figure 1: Left: Microbes at oil water interface. Right: The meniscus has a function of time. Three numerical experiments have been performed, one in which the drops would be attracted to the wall (Microbes W), microbes not attracted (Microbes NW) and one where the mass of microbes where neglected (Microbes NG W).

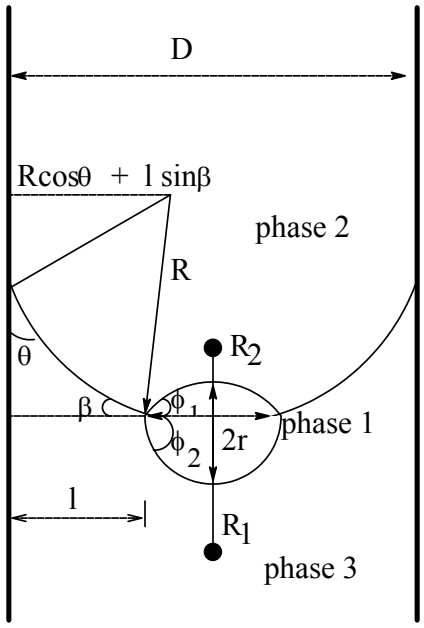

Figure 2: Drop inside a capillary tube of diameter D.

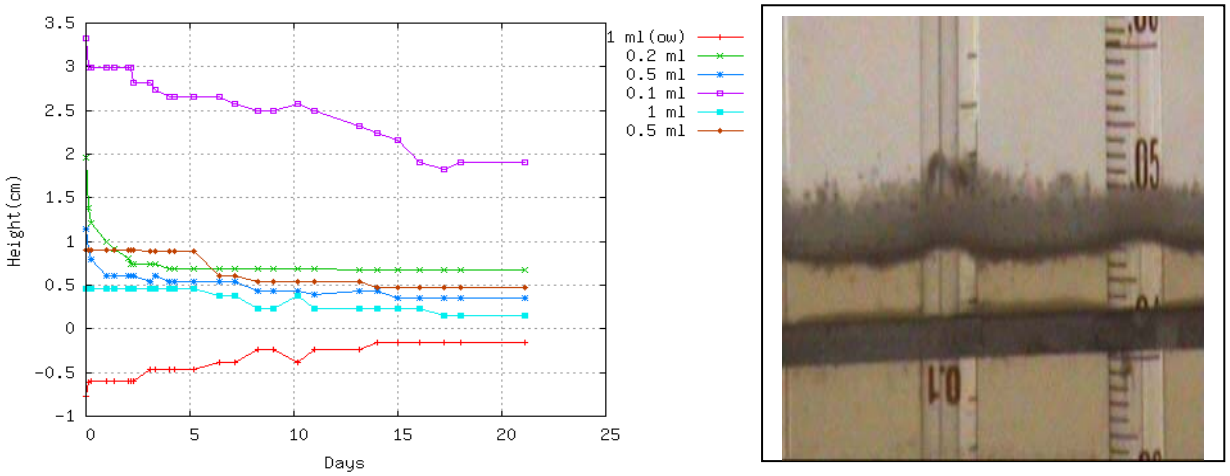

Figure 3: Left: Height of oil water meniscus as a function of time for *Bacillus Lichenformis*(left). Right: Picture of biofilm between the tubes in the model

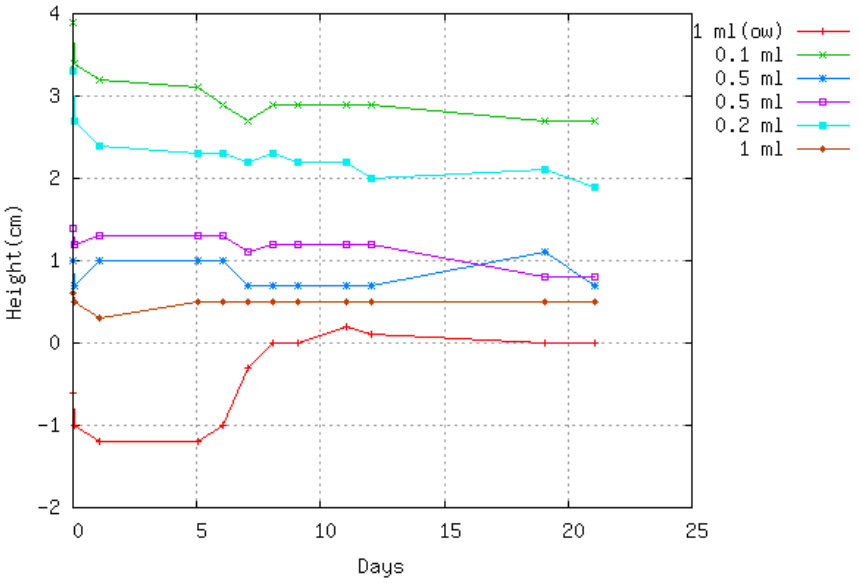

Figure 4: Height of oil water meniscus as a function of time, the microbes is anaerobic microbes from a North Sea oil reservoir.

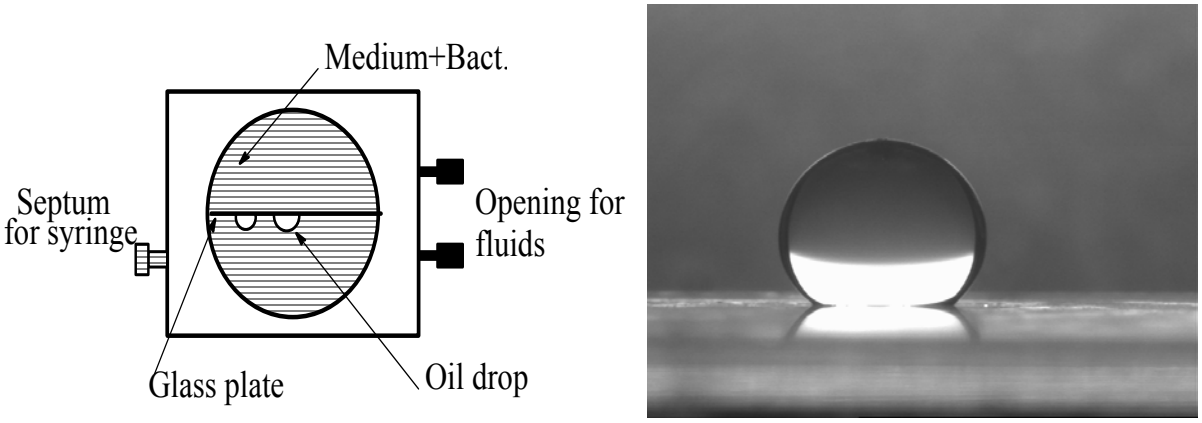

Figure 5:Left: Drawing of the anaerobic cell for measuring contact angle. Right: Picture of an oil drop resting on the plate.

Table 1: Microbial reaction products and their claimed effects for EOR (Momeni (1990))

Products	Effects
Acid	Increase rock porosity and permeability. Produce CO_2 via reaction with carbonate minerals.
Biomass	Selective and nonselective plugging. Emulsifaction through adhesion to oil. Changing wettability of mineral surfaces. Reduction of oil viscosity and pour point. Desulphurization of oil.
Gases	Reservoir repressurization. Oil swelling Viscosity reduction. Increase permeability due to solubilization of carbonate rocks.
Solvents	Dissolution of oil
Surfactants	Lowering of interfacial tension. Emulsification.
Polymers	Mobility control. Selective or nonselective plugging.