

# **SURFACTANT ENHANCED GRAVITY DRAINAGE: LABORATORY EXPERIMENTS AND NUMERICAL SIMULATION MODEL**

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## **1. ABSTRACT**

Oil recovery from fractured oil-wet and mixed-wet carbonate reservoirs by water flooding is generally poor. Injected water preferentially flows through the fractures and by-passes most of the oil in the matrix. For the water to displace oil from the matrix, a pressure drop needs to be created at the fracture-matrix interface that exceeds the capillary entry pressure which is significant especially for low permeable and oil-wet rock matrix. In the last decade, surfactant flooding has emerged as a potential EOR method to improve oil recovery from fractured carbonate reservoirs. Surfactant can improve oil recovery by either altering the wettability of the matrix and enhances spontaneous imbibition of water or reducing interfacial tension between oil and water and thus enhances oil-water gravity drainage or both. The focus of this paper is on understanding the surfactant enhanced gravity drainage (SEGD) process.

In laboratory experiments using core samples the balance between gravity and capillary forces often differ from that in the field. The experiments take long time, up to weeks or months, and at this time scale it is difficult to separate the effect of molecular diffusion and gravity. Therefore, we have used the centrifuge technique to 1) increase the gravity to be more representative of field scale and 2) make convective flow driven by gravity faster than diffusion. This will provide evidence as to whether SEG D is limited by diffusion.

The centrifuge experiments were performed using carbonate core samples (limestone) aged to restore wettability. Both spontaneous imbibition experiments and multi-speed centrifuge experiments were performed with and without surfactant. The objectives of the experimental program are: 1- measure imbibition water-oil capillary pressure with and without surfactant which is used for reservoir scale simulation; 2- measure oil recovery by surfactant enhanced gravity drainage using field representative capillary/gravity force ratio; 3- understand the effect of connate water on the efficiency of the SEG D process and 4- investigate whether the process is limited by diffusion.

## **2. INTRODUCTION**

Carbonate reservoirs contain approximately 60% of the world's oil reserves. Many carbonate reservoirs are naturally fractured and oil-wet/mixed-wet. In the presence of a connected fracture network, water flooding is not effective as water will preferentially flow via the fractures and little oil is produced from the matrix. In these kind of reservoirs, water must overcome a capillary entry pressure or capillary barrier in order to displace oil from the matrix. This capillary entry pressure can be in the order of a few psi for low permeability rock. Surfactant injection is an EOR technique that aims at reducing capillary forces between oil and water and thus enhances gravity drainage in fractured oil-wet reservoirs or reduces residual oil saturation to water flooding in matrix dominated reservoirs. Surfactant enhanced gravity drainage (SEGD) has emerged in the

last decade [Adibhatia. et. al. 2005, 2007 and 2008, Gupta and Mohanty 2007, Hirasaki and Zhang 2004] as an improved recovery technique for such oil-wet/mixed-wet fractured carbonate reservoirs. Surfactant enhanced gravity drainage (SEGD) is a process which is different from conventional surfactant flooding or alkaline-polymer-surfactant flooding. The target for SEG D is un-swept/un-drained oil in the matrix while for conventional surfactant or ASP process the target is to reduce the waterflood remaining oil saturation. Moreover, in SEG D there is no need for an ultra low IFT between surfactant solution and crude oil and no need for mobility control which is provided by the polymer in the conventional ASP process. A reduction in IFT in the order of  $\sim 10$ -20, would cause gravity force to exceed the capillary pressure of the matrix block. Therefore, to model such a process at reservoir scale, capillary pressure between surfactant solution and crude oil needs to be measured in addition to water-oil capillary pressure. The surfactant used in this work does not alter wettability of the core samples from oil-wet to water-wet at the experimental conditions, so the process relies on IFT reduction. Using the centrifuge, the gravity drainage process can be accelerated which helps to distinguish between the effect of gravity and diffusion.

In the literature, experiments have been reported on the measurement of either residual oil to surfactant solution in both secondary or tertiary flooding experiments or oil production in gravity drainage experiments. The latter is performed by placing oil saturated samples in a core holder surrounded by surfactant solution and recording oil production as a function of time. Oil can be produced by either wettability alteration [Standnes et. al. 2002, Strand et. al. 2003 and Hognesen et. al. 2004] or gravity drainage due to reducing the IFT or both. These experiments usually take long time and it is difficult to separate the effect of spontaneous imbibition due to wettability alteration from gravity drainage. One more issue of importance to both wettability modification or SEG D is the impact of connate water on the efficiency of these processes. If connate water (or initial water) banks in front of the surfactant solution, the water bank will form a buffer that separates surfactant from the oil and reduces the efficiency of the surfactant enhanced EOR techniques. However, as the developed water bank is initially very thin, diffusion can still be fast enough such that surfactant can be at the front of the water bank, especially in cases of limited adsorption. As pointed out by Adibhatia and Mohanty (2008), capillary or gravity scaling groups developed in the literature may not be directly applicable to scale up this process from the laboratory to the field. Appropriate numerical simulation, capturing the correct physics, should be used to scale up the process to field scale, including the effect of both diffusion and gravity forces.

### **3. EXPERIMENTAL PROCEDURE**

A large set of imbibition oil-water capillary pressure curves has been generated in the last few years [Masalmeh et. al. 2003, 2006, 2007]. In this paper we present the capillary pressure curves measured between the crude oil and surfactant solution using the centrifuge technique on 10 carbonate core samples and compare the results with the corresponding water-oil  $P_c$  curves. The characteristics of the samples are shown in Table 1. Plugs 1-8 contain connate water while plugs 9 and 10 contain no initial water saturation. Synthetic reservoir brine was used in the experiments which is referred to as water in this paper. All samples either with or without initial water saturation were aged for 4 weeks to restore wettability.

The centrifuge can run in two modes; 1- use a sleeve to seal the sides of the core samples and force flow from the inlet and outlet only, or 2- all the sides of the core are open to flow and the displacing fluid surrounds the sample from all sides. Different

concentrations of surfactants have been used in the experiments, from 0.1% to 1 wt%. Different cycles of drainage and imbibition experiments have been performed in this study, however, in this paper we will only report the first imbibition cycle (i.e., water displacing oil).

Numerical simulation has been used to interpret all experimental data using 1D and 2D models. The 2D model was used to investigate the impact of the flow from the sides of the samples (in addition to the inlet and outlet ends) on the measured Pc curves or oil production.

In addition to capillary pressure measurements, interfacial tension between surfactant solution and crude oil was measured as a function time and surfactant concentration. These measurements have been used to test the stability of the surfactant as a function of time. Cationic surfactant DTAB (also known as C<sub>12</sub>TAB) has been used in all experiments reported in this paper.

## 4. RESULTS AND DISCUSSION

The centrifuge experiments were designed such that no recovery is obtained at the lowest rotation speed when water without surfactant was the displacing fluid, i.e, the gravity force at low speeds is lower than the water-oil capillary entry pressure. In the surfactant experiments, the oil recovery process starts once the surfactant reaches the oil-water interface. The capillary forces will then be reduced due to the low interfacial tension and oil will be displaced by gravity.

The extent of oil recovery depends on the balance between gravity and capillary forces. Once capillary force is reduced such that gravity is dominant for most of the saturation range (for all pores that contain movable oil), any additional reduction in IFT may not lead to extra oil production although it can still lead to faster recovery. In a gravity drainage process, no reduction in residual oil to water is expected as gravity force is relatively low and even with reduced IFT the Bond number ( $N_B = \Delta\rho g L^2 / \sigma$ ) will still be  $<10^{-6}$ .

### 4.1 Connate Water Banking

As discussed in the introduction, the presence of connate water can have a major impact on the efficiency of the process. Connate water is expected to either 1) bank in front of displacing water, 2) mix with it or 3) be by-passed. The data published in the literature suggests that all the connate water in the pore space is displaced by injected water but with some degree of mixing [Jerauld et. al. 2006 and references therein]. However, in the reported data, injected water was either the same as connate water, different salinity water or high viscosity water, but not with a surfactant solution. As surfactant water is injected, a water-oil interface will experience different capillary forces compared to a surfactant water-oil interface. Moreover, the published data is measured in viscous dominated experiments where viscous forces dominated both gravity and capillary forces. In a gravity stable experiment, especially when gravity forces are lower than the water-oil capillary forces, injected surfactant water may follow a different path in the pore network and by-pass the connate water, as discussed below.

The imbibition surfactant water-oil Pc is expected to be lower (scaled with IFT) than the water-oil Pc. However, as the sample has connate water, the part of the sample where water is in contact with the oil will follow the water-oil Pc curve and the part where surfactant solution is in contact with the oil will follow the surfactant water-oil Pc

curve. Therefore, it is important to understand the effect of connate water on the measured oil recovery and surfactant water-oil Pc curve.

***Connate water banks in front of the surfactant water:*** In this case surfactant will have initially no contact with the oil in the sample as connate water will form a buffer that separates oil from surfactant and no oil recovery is expected at low centrifugal speeds. The displacement will follow the normal water-oil Pc curve. However, diffusion can bring the surfactant to the front of the water bank especially since the bank is initially very thin due to the low connate water saturation. In the laboratory experiments performed at normal earth gravity (1g), using few centimeter long core plugs, diffusion is fast enough to keep the surfactant at the water-oil interface. In such kind of experiments, diffusion will not be a limiting factor. However, once we increase the gravity force, diffusion can be a limiting factor that hampers oil production if connate water with no surfactant banks ahead of displacing water.

***Surfactant water mixes with connate water:*** In this case connate water bank develops in the porous medium but injected surfactant water mixes with connate water. In addition, diffusion may also contribute to bringing the surfactant to the water-oil interface. The measured capillary pressure will then depend on the IFT between the diluted surfactant (due to mixing with connate water) and the crude oil. Significant IFT reduction can still be encountered even at low surfactant concentration, and the effect of connate water may not be noticeable in this case especially at laboratory scale experiments.

***Surfactant water by-passes connate water:*** Depending on the balance of gravity, capillary and viscous forces, surfactant solution can by-pass connate water and contact crude oil directly as connate water has low mobility and that oil occupies most of the pore space especially the large pores. In this case the surfactant solution will experience reduced capillary forces (scaled with IFT) and oil will be displaced by buoyancy. The process will not be limited by diffusion and the speed of the process will depend on the balance between gravity and the “reduced” capillary forces.

This case needs further examination. In the centrifuge experiment, the displacing surfactant water will experience lower interfacial tension (and hence low capillary force) with crude oil than that between connate water and crude oil. At low speeds where gravity is still lower than water-oil capillary entry pressure but higher than the surfactant water-oil entry pressure, oil cannot be displaced by any mobilized connate water. In this case, either no oil production will take place or surfactant water will displace the oil directly or production will not start until surfactant diffuses through the connate water and then displaces the oil. The path of least resistance is for the surfactant water to displace oil directly. Experimental data can verify whether the process is controlled by diffusion from the rate of oil production at low centrifugal speeds, as will be discussed below.

The centrifuge experiment is carried out at different fixed centrifugal accelerations. Oil is displaced when the centrifugal force exceeds the capillary force which is retaining the oil in the largest pore (where pore neck radius is  $r_1$ ). Oil production will cease once equilibrium is reached between capillary and centrifugal forces, i.e., the centrifugal force is equal to the capillary force retaining oil in a pore with radius  $r_2$ , which is smaller than  $r_1$ . If no wettability alteration takes place ( $\theta$  is constant), the entry pressure for the surfactant solution as compared to the normal water is:

$$P_{c\_so} = \frac{\sigma_{so}}{\sigma_{wo}} P_{c\_wo}$$

where  $P_{c\_so}$  is the entry pressure (also known as the displacement pressure) for the surfactant solution,  $P_{c\_wo}$  is the entry pressure for normal water,  $\sigma_{so}$  is the surfactant solution-oil IFT and  $\sigma_{wo}$  is the water-oil IFT.

The required gravity force to displace oil by surfactant solution is much lower than that by water alone. As already shown in Masalmeh and Jing (2006 and 2007), the water-oil entry pressure of low permeability samples ( $K < 10$  md) is in the order of 2-4 psi. For surfactant solution this entry pressure will be reduced by a factor of 10-20, depending on the IFT reduction between surfactant and crude oil. At a low speed, no oil production should be observed if connate water banks in front of the surfactant water unless surfactants diffuse to the water-oil interface. In the actual water-oil centrifuge experiment, indeed no oil was produced at low speeds until the entry pressure was exceeded. However, in the surfactant water-oil experiment, oil was produced at very low speed of 500 rpm, which is equivalent to a capillary pressure of 0.43 psi. This shows that surfactant came in direct contact with the crude oil by one of the three mechanisms discussed above (i.e., diffusion through connate water bank, connate water mixes with surfactant water or surfactant water by-passes connate water).

Surfactant diffuses as a result of a concentration gradient within the same solution. Therefore, surfactant will diffuse from the surfactant solution to the connate water by random Brownian movement of molecules. Appelo and Postma (2007) measured diffusion coefficients of several ions in free water and found that it is almost constant  $\sim 10^{-9}$  m<sup>2</sup>/s. However, in porous media molecular diffusion is slower and molecules have to travel an extra distance to circumnavigate the grains. As shown by Appelo and Postma (2007), the effective diffusion coefficient in porous medium is calculated from the “free” diffusion coefficient as follows:

$$D_e = D_f * \varphi$$

where  $\varphi$  is the porosity of the porous medium,  $D_f$  is the free diffusion coefficient and  $D_e$  is the effective diffusion coefficient in porous medium. For a porous medium at connate water the diffusion is expected to be lower as the water saturation is low. For a porous medium of 0.25 porosity, the diffusion coefficient is about  $2.5 \times 10^{-10}$  m<sup>2</sup>/s. The effective (water filled) porosity of a core at connate water of 10% (the volume occupied by water to the total pore volume) is 0.025 which reduces the diffusion coefficient by another factor of 10. In mixed-wet or oil-wet porous media where not all connate water is connected and as the water occupies mainly small pores, the diffusion coefficient is reduced even further. Therefore, the effective molecular diffusion coefficient for oil-wet/mixed-wet tight carbonate is in the order of  $\sim 1 \times 10^{-11}$  m<sup>2</sup>/s or lower. In the following section we will discuss whether the experimental data can be explained by such a low diffusion coefficient.

#### 4.2 Surfactant Stability

The solubility of the surfactants was tested in the high salinity brine ( $\sim 200,000$  ppm) and at high temperature. The surfactant was aged together with crude oil at 120 °C with IFT measurements performed at different temperatures from ambient to 90 °C. The measured IFT data as a function of aging time show that the IFT of C<sub>12</sub>TAB is stable and weakly dependent on the surfactant concentration in the range tested in the

experiment (0.05% - 1%). The IFT value of  $C_{12}$ TAB/oil is about a factor of 15 lower than that of water-oil.

### 4.3 Numerical Simulation

A MoReS (Shell in-house simulator) model was built to simulate the effect of the different parameters on SEGD and to history match the centrifuge experimental data. A 1-D model to history match centrifuge experiments was previously presented by Maas and Schulte (1997). In the present study we built both 1-D and 2-D models that include diffusion, radial flow effects and the dependence of the  $P_c$  curve on the surfactant concentration. The grid size is  $\sim 2$  mm in the x-direction (for the 2-D model) and 1 mm in the z-direction (for both 1-D and 2-D models). In the 2-D model we have two options, no flow boundary to prevent flow from the sides or all the faces are open to flow. In the latter case, surfactant solution surrounding the plug from all sides can enter the core from the side as well as from the inlet face while oil will leave from the outlet face.

In the simulation runs, the water-oil imbibition  $P_c$  is first assigned to all grid blocks that contain connate water. The capillary pressure will then be switched to the surfactant water-oil  $P_c$  curve as a function of surfactant concentration. To simplify the model we have used two capillary pressure curves, one for water-oil and one for surfactant water-oil. The  $P_c$  in a grid block is switched to the surfactant-oil  $P_c$  curve as the surfactant concentration in that grid block exceeds a critical surfactant concentration  $S_{sc}$  (0.05%, see below). The simulation assumes complete connate water banking, therefore surfactant can only diffuse through the connate water to enter a grid block and then the  $P_c$  curve will be switched to the surfactant water-oil  $P_c$  curve. The surfactant does not change the wettability of the rock as shown by spontaneous imbibition experiments, therefore, the magnitude of the negative capillary pressure is only reduced due to the low IFT between surfactant water and crude oil. The residual oil saturation was found not to be affected by the addition of surfactant in these experiments: the centrifuge data with and without surfactant resulted in the same residual oil saturation. The relative permeability is also not affected by the surfactant, as the IFT value between surfactant solution and crude oil is not low enough to cause 2-3 orders of reduction in the Bond number.

In the history matching exercise, there are three degrees of freedom, the critical surfactant saturation at which the  $P_c$  curve will be switched to surfactant water-oil  $P_c$ , the diffusion coefficient and the reduction factor in the  $P_c$  curve. Experimental data (both IFT measurements and centrifuge data) suggests that the critical surfactant concentration is within the range of 0.02-0.05%. The experimental data shows that the IFT is almost constant for surfactant concentration higher than 0.05%. As surfactant adsorption was ignored in context of this work, 0.05% was used as the critical surfactant saturation.

#### 4.3.1 Effect of Initial Surfactant Concentration

Figure 1 shows the centrifuge production data of different samples using different surfactant concentrations. The data shows that both the rate and volume of oil recovered at low centrifugal speed increase as surfactant concentration increases. Increasing the surfactant concentration to higher than 0.5% does not lead to additional oil recovery. The data shown in the figure appears to be contradictory to the IFT data, i.e., constant IFT should lead to the same reduction in capillary forces and hence the same recovery over this surfactant concentration range. However, the critical surfactant concentration

needed to change the Pc curve can be achieved much faster for the high surfactant concentration due to either diffusion, mixing with connate water or convective flow. Therefore, higher and faster recovery can be obtained when higher surfactant concentration is used even when using the same Pc curve. To illustrate this point, Figure 2 shows simulated centrifuge data using the same capillary pressure curves but with different surfactant concentrations. Similar to the experimental data shown in Figure 1, the rate and volume of oil recovery at the first speed increases with surfactant concentration up to 0.5%. Increasing the surfactant concentration further does not affect the oil production curve. At higher speeds, all the curves converge with no dependence on surfactant concentration. This is explained by the fact that the critical surfactant concentration is already reached in all grid blocks by that time and the Pc curve has already switched to the surfactant water-oil Pc. Although the trend in both figures is the same, there is still some difference which is attributed to the fact that the experimental data is measured on different samples with different capillary pressure characteristics while the simulated data is performed using the same plug characteristics but with varying the initial surfactant concentration.

#### 4.3.2 Effect of Flow from the Sides of the Samples

The 2-D model was used to investigate whether keeping the sides of the plug open will lead to different recovery curves. Figure 3 compares experimental data measured using two samples, the one with the sides open shows higher rate and recovery than the one with the sides close to flow. However, the one with the sides open has also higher permeability which contributes to the higher recovery at the same centrifugal speed due to the lower capillary pressure. To make a direct comparison, we have run the simulation models with the sides open or close. Numerical simulation was first performed where both connate water and displacing water are the same, i.e., no surfactant is used. In this case, the same Pc curve is used throughout the simulation run and no difference is observed whether the sides are open or close. A 1-D model can capture fluid flow behavior in this experiment and there is no need for running 2-D or 3-D models.

The results are different when the sample is surrounded by surfactant water, see Figure 4. For the case where the sides are open, surfactant solution can enter the core sample from the side and increase the oil recovery, especially at an early time in the experiment. This leads to an inhomogeneous saturation profile where the water-front moves faster at the sides and it lags behind in the center of the core. Later in the experiment, both runs converge as now surfactant reaches all grid blocks and the Pc will be switched to the reduced surfactant water-oil Pc curve throughout the model.

#### **4.4 History Matching Experimental Data**

History matching of the centrifuge data was first attempted using a diffusion coefficient of  $1 \times 10^{-11} \text{ m}^2/\text{s}$ . No history match was obtained with such a low value. A history match was obtained using a diffusion coefficient of  $1 \times 10^{-10} \text{ m}^2/\text{s}$ , see Figure 5. The same diffusion coefficient was used to match all experimental data which is an order of magnitude higher than what is expected for molecular diffusion in porous medium at connate water. Figure 6 shows examples of the surfactant water-oil Pc curves compared with the water-oil Pc curves measured on the same samples. The data is shown as a function of scaled water saturation  $S_w^* = (S_w - S_{wc}) / (1 - S_{or} - S_{wc})$ . In general a reduction factor between 12-17 was found for all the samples used in the study, which is consistent with the IFT ratio between water-oil and surfactant water-oil.

This result rules out the possibility of a connate water bank as a buffer between surfactant and oil. A water bank would either lead to no impact of surfactant on the centrifuge production data (hence the Pc curve) or the process would be limited by the molecular diffusion coefficient. For comparison, Figure 5 shows the simulated centrifuge data with a diffusion coefficient of  $1 \times 10^{-11} \text{ m}^2/\text{s}$ . The oil recovery at low centrifugal speed is lower and slower. The results show that surfactant comes in contact with crude oil much faster than what molecular diffusion predicts. Using a diffusion coefficient higher than  $1 \times 10^{-10} \text{ m}^2/\text{s}$  did not make any impact on the modelled oil recovery at each centrifugal speed, which shows that the “effective” diffusion can still be higher but our experiments can not determine this effect.

The high “effective” diffusion coefficient is a result of either 1) mixing of surfactant solution with connate water, 2) by-passing of connate water or 3) a faster diffusion driven by the IFT gradient. From our presented experiments we cannot conclude which of these (isochronically occurring) effects dominate and dedicated experiments are needed to isolate and measure these different effects directly. We have performed centrifuge experiments where no connate water was present in the core samples and gravity is the only driving force. Two samples were fully saturated with oil. Surfactant solution was then used as the displacing fluid in the centrifuge. The Pc curves used to history match the experimental data is compared to that used to history match the experiments where connate water was present, see Figure 7. For proper comparison, only samples with similar porosity, permeability and drainage Pc curves are shown. The imbibition Pc curves are very similar, which indicates that the presence / absence of connate water had no effect on the measured Pc curve between surfactant solution and oil. This result confirms two conclusions that have important consequences on the understanding and the efficiency of the SEG D process: 1- Connate water did not form a buffer in front of the displacing surfactant water and 2- Molecular diffusion is not a limiting factor for this process.

#### **4.5 Mechanism of Surfactant Enhanced Gravity Drainage**

The experimental data presented in this paper demonstrates that surfactants significantly enhances oil-water gravity drainage in fractured reservoirs and that the SEG D process (on the core scale) is an order of magnitude faster than expected by molecular diffusion. This makes the process more promising than suggested by earlier studies in the literature. Adibhatia and Mohanty (2008) argued that diffusion plays an important role as the surfactant needs first to penetrate the matrix in order to reduce interfacial tension and diffusion can be a limiting factor on field scale. The experiments reported in the literature were not designed to address this question. The gravity head in the laboratory experiments performed at 1g (earth gravity) is low and therefore diffusion is fast enough and does not limit the overall rate of the process. In our centrifuge experiments, gravity forces are much higher than 1g and therefore gravity and diffusion time scales can be easily distinguished.

In the following we discuss what happens at the pore scale. SEG D starts as a result of reducing the capillary forces at the matrix-fracture interface such that the pressure drop caused by buoyancy overcomes the reduced entry pressure and enables oil recovery from the matrix. The question is how can surfactant reduce the capillary pressure at the matrix-fracture interface. Diffusion is one possible mechanism. However, to reduce interfacial tension and hence capillary forces, it is not a pre-request for the surfactant to diffuse into the core sample in the laboratory or the matrix block in the reservoir. The



interfacial tension is reduced at the water-oil interface, and hence reduces capillary forces and enables the water to penetrate the matrix block. The water-oil interface is not inside the pores of the porous medium but at the entry of the pores. Figure 8 is a cartoon to explain this mechanism. On the microscopic scale, surfactant water surrounding the core sample will have direct contact with the oil at the entry of the pore. There is no need for the surfactant to diffuse into the pore space to change the interfacial tension. On the contrary, it penetrates the pore because of the lower interfacial tension at the entry of the pore. This suggests that the process is driven mainly by gravity forces and diffusion is not a limiting factor.

#### 4.5.1 Up-scaling to Reservoir Scale

Care is required when up-scaling these results to reservoir scale. Surfactant adsorption and mixing between connate water and invading water may lead to significant surfactant loss and/or dilution of surfactant concentration at the water front. For the SEG D process to continue and displace more oil from the matrix, a minimum surfactant concentration needs to be maintained at the water-oil interface. In the oil-wet rock, connate water is mainly in the small pores which have not been penetrated by oil during reservoir charging or in the corners of the big pores. When surfactant becomes depleted close to the oil-water interface, diffusion can play an important role in keeping the surfactant at the water-oil interface. The injected surfactant concentration boundary moves into the matrix because of flow caused by IFT reduction. Therefore, the distance for the surfactant to diffuse is much shorter which makes it much faster (time scale is proportional to  $L^2$ ) and more effective and may not significantly slow the process. Figure 9 shows the surfactant penetration profile in 2D for two cases after 50 hours. Figure 9a is for the case when water displaces the oil due to gravity (in the centrifuge) and Figure 9b is for the case where the water does not penetrate the core (gravity is lower than the entry pressure). In the first case the surfactant moved much further within the core, the same diffusion coefficient was used in both runs.

## **CONCLUSIONS**

Surfactant enhanced gravity drainage (SEG D) was investigated using the centrifuge technique. The focus was on understanding the mechanism of this process and the effect of connate water on its efficiency. The results show that:

- 1- The centrifuge technique is a useful tool to study the surfactant enhanced gravity drainage process and it helps to separate diffusion from gravity effects. It also allows to scale gravity forces to get similar response as in the reservoir.
- 2- The measured surfactant water-oil imbibition  $P_c$  curves scaled directly with the IFT reduction ratio to the corresponding water-oil  $P_c$  curves.
- 3- Initial water saturation showed little or no impact on the measured surfactant water-oil  $P_c$  curves.
- 4- The diffusion coefficient needed to explain the experimental results is a factor of 10 or more higher than molecular diffusion. The experimental data shows that molecular diffusion alone cannot explain the rate and volume of oil recovered by SEG D.
- 5- The data does not support the assumption of complete connate water banking in front of the injected surfactant solution. In a gravity stable process, connate water will either mix with or be by-passed by the displacing surfactant water.

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Table 1: Characteristics of the samples used in the experimental program

Plug id	L [cm]	D [cm]	Vp [ml]	Phi %	k_brine [md]	Swi	Sor
1	4.83	3.78	13.53	24.9	13.6	0.18	0.10
2	4.68	3.78	12.03	22.8	7.9	0.09	0.23
3	4.69	3.78	10.95	20.8	9.3	0.25	0.04
4	4.91	3.78	13.5	26.1	2.5	0.23	0.09
5	4.9	3.79	14.45	26.0	2.6	0.11	0.08
6	4.9	3.79	14.77	26.6	3.4	0.09	0.10
7	4.91	3.78	15.48	28.0	3.6	0.12	0.10
8	4.4	3.2	10.15	28.8	4.5	0.12	0.08
9	5.01	3.76	16.04	29.1	4.9	0	0.11
10	4.99	3.76	16.36	29.6	5.1	0	0.12

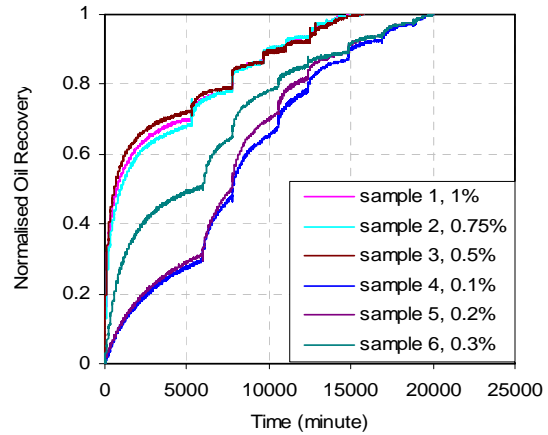


Figure 1: Normalised oil recovery for different samples at different centrifugal speeds using different surfactant concentrations.

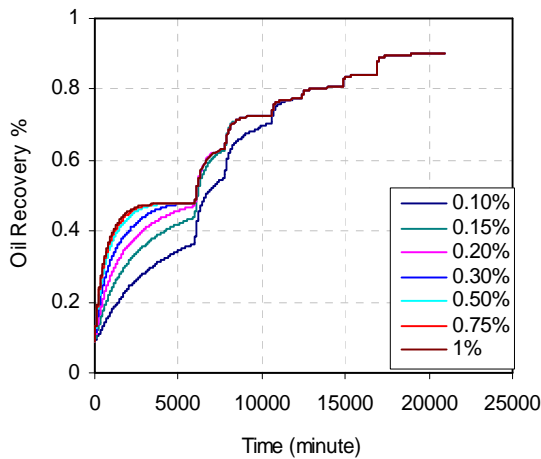


Figure 2: Simulated oil recovery for different samples at different centrifugal speeds using different surfactant concentrations.

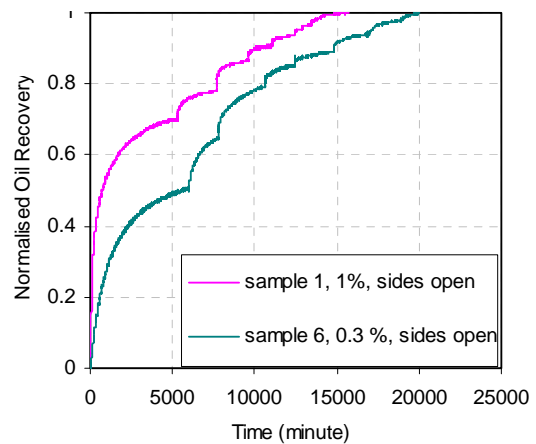


Figure 3: Normalised oil recovery for different samples at different centrifugal speeds, with sides open or closed.

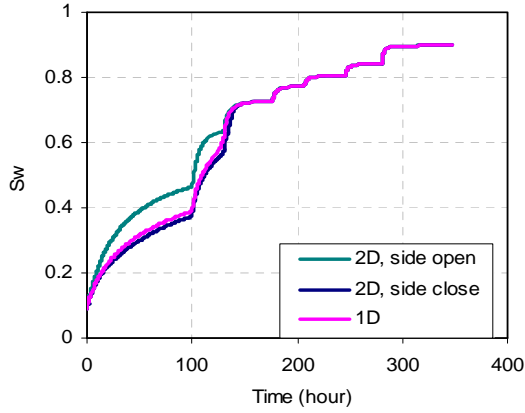


Figure 4: Simulated oil recovery for different samples at different centrifugal speeds, with sides open or closed. Also 1D simulation run is included

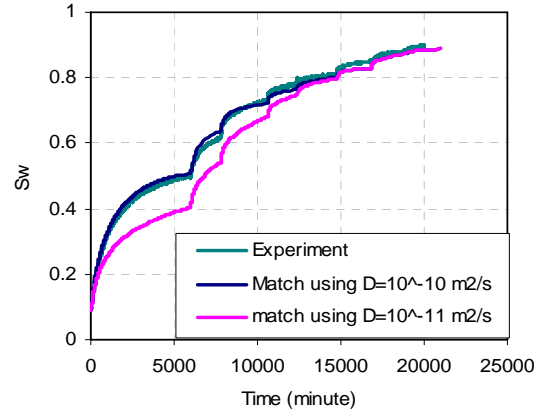


Figure 5: History match of centrifuge data using two different diffusion coefficients.

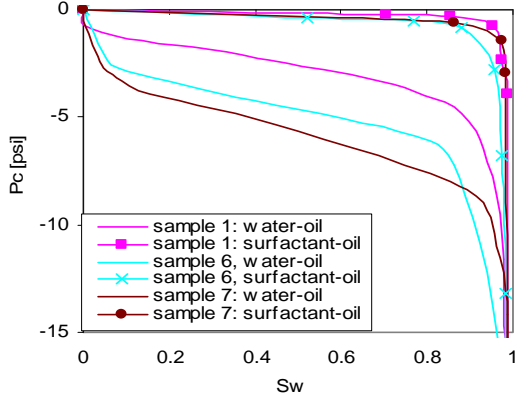


Figure 6: Pc curves with and without surfactant for 3 samples. Normalised water saturation is used on the x-axis.

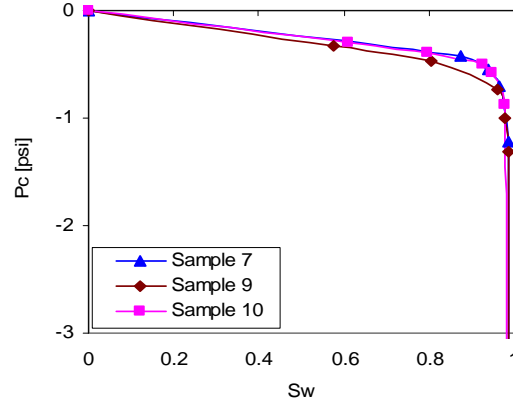


Figure 7: Surfactant-oil Pc curves measured with and without connate water. Normalised water saturation is used on the x-axis.

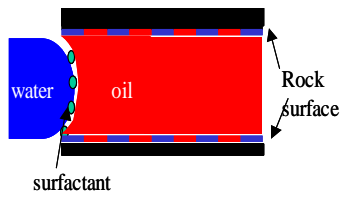


Figure 8: Cartoon showing how surfactant can reduce capillary forces without penetrating the core sample.

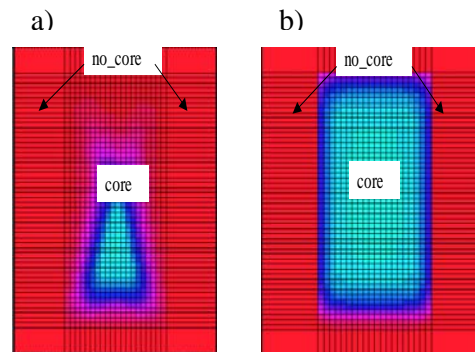


Figure 9: Surfactant profile in the core after 50 hours a) in centrifuge (high gravity 300-400 m/s<sup>2</sup>) and b) earth gravity (1g).