MECHANISTIC STUDY OF IMPROVED HEAVY OIL RECOVERY BY ALKALINE FLOOD AND EFFECT OF WETABILITY

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ABSTRACT
Alkaline flood, one of the oldest improved recovery techniques, is one of the most sensitive to reservoir parameters such as temperature, salinity level, wettability and hardness of the connate water. The aim of this study is to examine the performance of a specific alkaline/surfactant (AS) solution for improving recovery of a heavy crude oil by performing a series of visualisation experiments in high-pressure transparent porous media (micromodels).

In the first part of this study the pore-scale interactions, recovery mechanisms and efficiency of heavy oil recovery by AS flood are investigated. The results of these direct visualisation tests reveal the important role of a capillary driven flow mechanism (capillary cross-flow) to displace oil from high oil saturation regions of the porous medium towards the water channels where oil can be recovered through emulsification process. In the second part of this study, the effect of wettability of the system on oil recovery mechanisms of AS flooding is investigated. The results of our visualisation tests demonstrate the adverse effects of oil-wet porous medium on the efficiency of AS flood process and suggest remedies.

INTRODUCTION
The world's heavy oil resource is massive, but the development challenges also are huge and as a result only a small percentage of the global heavy oil resource can currently be developed economically. The most common heavy oil recovery methods are thermal techniques usually involving steam injection. However, steam injection is energy intensive with large environmental footprint. Additionally, steam injection cannot be applied economically to a large number of heavy oil reservoirs across the world especially deeper reservoirs or those with a thin pay zone (Donaldson 1989). Therefore, various alternative non-thermal recovery methods are being studied for producing heavy oil.

One promising non-thermal heavy oil recovery method is chemical injection. Caustic or more generally alkaline flooding is one of the oldest chemicals used for improving oil recovery. Alkaline flooding is a process in which the pH of the flood water is raised to a value around 10 and 12 by adding sodium hydroxide or other alkaline chemicals. (Labrid 1991; Green and Willhite 1998). The chemical interaction between alkaline materials and acidic species modifies the interfacial properties of the crude oil/water/rock system (Cooke et al. 1974). The natural surfactants of crude oil are believed to be the active agents in the process of oil recovery by alkaline. The mechanisms of the surfactant action during alkaline flooding have been studied in some detail however it is not yet fully understood. Essentially, their impact arises due to their adsorption at surfaces and interfaces, by which they alter surface electric charge and interfacial tension. Co-injection of surfactant can enhance the process of alkaline flood by increasing the optimum concentration of the alkali and hence improving its propagation through the porous medium, producing lower IFT and sustaining this IFT for a longer period (Nelson et al. 1984).

The recovery mechanisms of alkaline (or AS) flood has been studied extensively in the laboratory (Cooke et al. 1974; Jennings et al. 1974; Johnson 1976; Campbell 1982; Martin et al. 1985). The most commonly referred recovery mechanisms are IFT drop, wettability change and emulsification. Many field tests of alkaline or the combinations of alkaline and surfactant/polymer have been reported (Mayer et al. 1983; Green and Willhite 1998 Demin et al. 1999; Wyatt et al. 2002) which have revealed that alkaline flooding is not a simplistic method but if the project is designed and monitored carefully it is an economically viable technique for application in waterflooded fields (Labrid 1991; Wyatt et al. 2002). Recent studies on the recovery of extra-heavy crude oils by AS flood have shown good potential for this recovery process in conjunction with waterflood (Liu 2006; Bryan and Kantzas 2009).

This study presents the results of a series of flow visualisation (micromodel) experiments carried out on a particular heavy crude oil. The main objective of this work was to investigate the potential of a specific alkaline and alkaline-surfactant (AS) solution for improving the heavy oil recovery efficiency by investigating the underlying mechanisms and the effect of reservoir parameters on the AS performance.

EXPERIMENTAL FACILITIES

A high-pressure micromodel rig was used to perform the micromodel experiments. Details of the experimental facilities can be found elsewhere (Sohrabi et al. 2000).

Glass Micromodels

In this study, a heterogeneous and a homogenous rock-look-like pattern micromodels were used. The micromodel orientation was vertical with the inlet port at the top and the outlet at the bottom end of the model. Figures 1(a) and 2(a) show two magnified sections of the micromodels fully saturated with heavy crude oil (black colour) and Table 1 shows the dimensions of the micromodels and their pores. To show the images of the micromodel at a suitable magnification, only the image of a middle section of the micromodel, which is representative of the whole micromodel, is presented throughout this paper. The full width of the micromodel was open to flow and the yellow arrows on the images show the flow direction. As the depth of the pores of the micromodel is relatively uniform, by measuring the area occupied by different fluids using an image analysing software, the saturation of fluids within the model can be determined.

Fluids

Table 2 presents the basic properties of the highly viscous crude oil used in the micromodel experiments. Distilled water (DW) was used as the aqueous phase in all the micromodel tests. The AS solution was prepared using sodium hydroxide (NaOH) and an AOS (Alpha-Olefin- Sulfonate) surfactant at very low concentrations. The alkali was utilized at its critical concentration to attain ultra-low IFT at the test temperature. A professional desktop pH meter was used to measure the pH of the AS solutions before each experiments. The pH number of the AS solution was measured 5 times and the average value was equal to 12.

EXPERIMENTAL PROCEDURE

A very similar experimental procedure was followed in all micromodel tests reported here. However, different preparation techniques were used to simulate different wettability conditions. The micromodel was first saturated with DW and pressurised to 600 psig at 50 °C. To resemble the initial migration of oil in a water-bearing reservoir and to establish an initial oil and water saturation, the crude oil was then injected from the bottom end of the micromodel and continued until the oil front reached the other end of the porous medium. To simulated waterflooding of an oil reservoir, the model was then flooded with water for an extended period of time. The AS flood was carried out after this initial period of waterflood. Both water and AS solution were injected from the top end of the vertical micromodel at a very slow rate of 0.01 cm3/hr. The effect of gravity forces on the recovery process was assumed to be negligible as the density difference between the heavy crude oil and water is small. Also, the total height of the micromodel is not more than a few centimetres. Based on the very slow rate of injection used in these experiments, the capillary number was estimated to be 2.5E-7.

AS FLOOD AND EFFECT OF HETEROGENEITY

The first case study consisted of two micromodel tests and the main objective was to investigate the oil recovery mechanisms and efficiency by AS flood in the homogeneous and heterogeneous systems. The first test was performed in the micromodel with homogeneous pattern and the second test was carried out in the heterogeneous pattern micromodel. Figures 1(a) and 2(a) respectively show magnified sections of the homogeneous pattern micromodel (test 1) and the heterogeneous pattern (test 2) at the end of the period of oil flood. Since the viscosity of the oil was significantly higher than the resident water, the displacement process was very efficient with the crude oil displacing almost all the water present in the micromodel and leaving behind a very low water saturation.

Then, water was injected into the micromodel for an extended period of three days to simulate the process of waterflood for this crude oil. With the porous medium retaining its water-wet characteristics, the injected water was observed to flow mostly in the form of layers on the walls of the pores. Piston-type displacement mechanisms was also recognized in the pores where the water layers were not connected enough to support flow of water through film flow. As the water injection continued, oil recovery and changes in water and oil distributions continued too and more oil was produced. This behaviour has been reported before by Sohrabi et. al. (Sohrabi et al. 2008) which is believed to be due to the unfavourable viscosity ratio between water and oil phases which causes oil recovery at later times after breakthrough. Figures 1(b) and 2(b) respectively show the same magnified sections of the homogeneous pattern micromodel (test 1) and heterogeneous pattern (test 2), at the end of the period of water flooding. As can be seen, a relatively high oil saturation remained in the porous media in both cases as a result of the poor viscosity ratio between the oil and the injected water. Subsequently to this period of waterflooding, the AS solution was injected through the micromodel.

Oil Recovery Process by AS Injection in a Homogeneous System

The results of the first micromodel test show that the injection of the AS solution drastically increases the rate of heavy oil recovery in the micromodel compared to waterflood, especially in the early times of injection. For the conditions of our experiments, the process of oil recovery by AS flood takes place mostly in the first 10 hours of AS injection and slows down after that and almost stops after 16 hours of AS flood. This is due to the dynamic nature of IFT between the crude oil and the AS solution which increases to high values after this period (Rubin and Radke 1980). Another reason for deceleration of the oil recovery rate after the first 10 hours can be depletion of the oil phase from its acidic spices. Figure 1(c), 1(d) and 1(e) show the same magnified section of the micromodel after 2.5, 5 and 10 hours of AS flood. It is clear that the injected AS has initially displaced the residual oil in the centre of the micromodel and has gradually spread towards the right and left edges of the model. Our observation shows that in the homogenous systems the incremental oil recovery by AS injection can be attributed to two groups of mechanisms based on the order of their appearance time.

1. *IFT Reduction & Wettability change:* The first group of mechanisms, which initially cause remobilisation, and re-connection of the trapped oil consists of wettability change (to strongly water-wet) and interfacial tension (IFT) reduction. Only a few minutes after the arrival of the AS solution to the porous medium the redistribution of the trapped oil due to these two mechanisms was observed. The reduction of water-oil IFT could be visually recognised by the ease of fragmentation and coalescence of oil ganglia and displacement of the initially trapped oil droplets in small pore bodies. Wettability alteration to more water-wet conditions could also be visually recognized in the micromodel tests by the change of the shape of the oil blobs to a rounder pattern and shape and through direct visualization of contact angles. Since these two recovery mechanisms appear in the micromodel almost simultaneously it is difficult to identify their separate contribution to the additional oil

recovery during the caustic injection period. The combination of these two mechanisms enhances oil recovery by reducing the adhesion forces between oil and micromodel glass and reducing the capillary trapping forces. This initiates formation of a bank of oil in front of the injected AS solution.

2. *Emulsification:* Emulsification of the heavy crude oil in water was also observed but at a later time compared to the wettability alteration and IFT reduction mechanisms. In fact this mechanism is closely linked to and is a result of the pervious two mechanisms but since firstly, it makes a distinct oil displacement mechanism and secondly, it starts in a later time during caustic injection it should be considered separately. It appears that when a certain limit of IFT between water and oil is reached and under the conditions of strongly water-wet, the trapped oil ganglia start to move forming small droplets of oil in the AS solution. At later times, as the IFT between oil and the aqueous phase drops to lower values (due to the reaction between acidic components of the oil and alkaline material in the aqueous phase) the size of the oil droplets becomes smaller as well.

The contribution of these two groups of recovery mechanisms to oil recovery is different for light and heavy oils. In the light oils, where most of oil is trapped due to capillary forces and the acidic spices in the oil phase are not enough to make ultra low IFT values, IFT drop and wettability alteration towards increased water-wet conditions are responsible for most of the additional recovery. However, as the oil becomes heavier the emulsification process plays a more important role in the oil recovery process. In the current test, using an extra-heavy crude oil, most of the incremental oil recovery was attained through emulsification process.

Oil Recovery Process by AS Injection in a Heterogeneous System

In the heterogeneous micromodel, the connectivity of the left hand side of the micromodel is considerably higher than the right hand side. Therefore, the injected AS flowed primarily in the left side of the micromodel displacing oil in that region and later spread to the right side towards the pores with lower connectivity. This caused the oil recovery mechanisms to be completely different in the right and left hand sides of the micromodel. On the left side of the micromodel (high connectivity region) the recovery mechanisms were quite similar to the case of the homogeneous system. The arrival of AS solution resulted in IFT reduction and wettability modification towards increased water-wet conditions. It was subsequently followed with emulsification mechanism which displaced the residual oil in form of oil/water dispersions. However, the residual oil in the right hand side of the micromodel was observed to be produced through a two-stage recovery process involving capillary cross-flow and emulsification mechanisms.

Step1: Capillary Cross-Flow: While the residual oil on the left side of the model was being produced by emulsification mechanism, the ultra-low IFT values in this region compared to the (high) IFT values of the uncontacted regions in the centre and right side of the porous medium generated a pressure gradient across the micromodel for the non-wetting phase (oil phase). Therefore, the oil in the poorly connected (uncontacted zone) of the micromodel was pushed towards the invaded zone where IFT between oil and alkaline solution was much lower. Figure 3 schematically illustrates this process of oil production from the low connectivity regions of the micromodel. The red arrows in the centre of this Figure show direction of the flow of the oil phase as a result of the capillary cross-flow mechanism. At the same time as the oil was flowing towards the invaded zone in the left side of the model, it was replaced by AS solution entering the pores in the centre and right hand side of the model through layers of water on the pore walls. This in turn improved water-wetness of the system and subsequently assisted the capillary drainage of the oil. The blue arrows in the Figure 3 show direction of the counter-current flow of the AS solution.

The capillary cross-flow becomes an important recovery mechanism in the case of heavy oils because the displacement of the residual oil in the uncontacted region of the porous media around the water channel cannot be accomplished by forced displacement. This recovery mechanism is very similar to the capillary imbibition mechanism observed in the fractured reservoirs which assists drainage of oil from matrix to the fractures (Firoozabadi and Markeset 1992).

Step2: Emulsification: The oil which moved from the initially uncontacted regions of the micromodel to the left hand side of the model supplied fresh components to react with alkaline and produced surfactants as soon as it came in contact with AS solution and was itself produced through emulsification in the aqueous phase. The vertical red arrows on the left hand side of Figure 3 show this stage of the recovery process. Finally, as the oil saturation in the right of the micromodel decreases, the flowing path of AS solution further developed towards the right side of the model where it displaced the rest of the residual oil through emulsification mechanism.

Figure 2(c), 2(d) and 2(e) show the same magnified section of the micromodel respectively after 2.5, 5 and 10 hours of AS flood. It can be seen that AS initially opened a narrow path at the very left side of the micromodel (Figure 2c) where the connectivity is higher, then the flowing path of AS solution gradually grows and spreads towards the right side of the micromodel with lower connectivity (Figure 2d). After 10 hours of AS injection the AS has invaded the entire micromodel producing the remaining oil with emulsification process (Figure 2e). Displacement of the residual oil towards the flowing path of alkaline by capillary-cross flow mechanism is apparent in Figures 2(c) and 2(d).

Comparison of the Homogeneous and Heterogeneous Systems

The comparison of the results of AS flood in homogeneous and heterogeneous micromodels indicates that in the homogeneous porous medium, where the injected solution has better access to different parts of the micromodel, oil recovery takes place mostly through emulsification process (direct displacement) while in the heterogeneous pattern micromodel, the capillary cross-flow of oil plays a very important role in the recovery of the residual oil especially from the low connectivity parts of the model.

We believe that the heterogeneous model is a better representative of the conditions of real reservoirs. In the heavy oil reservoirs due to the poor viscosity ratio between the water and oil, fingering of the injected water is a common issue. This causes the existence of regions with high oil saturation around the channels of flowing AS solution very similar to the process simulated by our heterogeneous micromodel experiment. Therefore, the effect of AS flood on capillary cross-flow should be considered more carefully for heavy oils.

EFFECT OF WETTABILITY

In the second part of the study, a number of flow visualisation tests were performed to investigate the effect of wettability (strongly water-wet, weakly water-wet, weakly oil-wet, strongly oil-wet) on AS flood performance and also to study the effect of AS injection on wettability of the porous medium. Although glass is naturally water-wet, during the acid etching process the micromodels become oil-wet and unless they are thoroughly cleaned in an ultrasound bath in a strong high pH surfactant, they remain oil-wet. The micromodel that we used in this work for the oil-wet experiments had not gone through the ultrasound cleaning after the acidizing process and was initially oil-wet. However, during the experiments and as it came in contact with alkaline solutions it gradually became weakly oil-wet and then weakly water-wet.

The results of our micromodel tests revealed that wettability can have a profound effect on the efficiency of oil displacement by AS. It was observed that as the system became less water-wet and shifted towards oil-wet conditions the incremental oil recovery by AS injection decreased drastically. Figures 4(a) shows a magnified section of the heterogeneous pattern micromodel at the end of the period of oil flood in the strongly oil-wet system. Figure 4(b) presents the same section at the end of the period of waterflood. The piston type displacement of oil by water and the presence of spreading oil layers on the micromodel surface confirm the oil-wet conditions in the micromodel. Figure 4(c) illustrates the same section of the micromodel at the end of the period of AS flood. Comparison of this Figure with Figure 4(b) shows that very small part of the residual oil (around 2%) has been produced during the extended period of AS flood in this oil-wet experiment. Similarly, in the cases of weakly-wet systems (weakly water-wet and weakly oil-wet), the incremental oil recovery due to AS flood was significantly less than water-wet experiments.

Effect of Wettability on Recovery Mechanisms

Based on our visualisation experiments, oil recovery by AS flooding is adversely affected if the porous medium is oil-wet mainly through two mechanisms:

1. The emulsification process which was the main displacement mechanism for heavy oil recovery in water-wet porous media significantly weakens in oil-wet systems as the oil has a high tendency to attach to the solid surface. Hence, despite very low interfacial tension between oil and AS solution very small portion of the oil will be produced by emulsification process in oil wet systems.

2. Oil displacement by capillary cross-flow which was one of the features of water-wet systems does not happen as the positive capillary forces and pressure gradient in the oil phase does not exist when oil is the wetting phase. This causes a significant fraction of oil remains unswept in the pores with low connectivity, in our experiments, in the centre and right hand side of the model.

Effect of AS Solution on Wettability Change

It is generally accepted that elevating the pH of the aqueous phase by injection of alkaline can alter wettability of the crude oil/water/rock systems towards more water-wet. Our observations made during alkaline flooding of intermediate heavy oils (lighter than the oil used in this study) have also confirmed this behaviour in which the wettability of the oil-wet micromodel shifted towards strongly water-wet conditions. However, the micromodel tests reported here show that for extra heavy crude oil used in this study, the AS solution was unable to effectively change the wettability of the oil-wet system to strongly water-wet conditions.

To explain this observation, we need to look at the basis of the wettability alteration process. The change in wettability at high pH is often attributed to chemical reactions between alkaline materials in the aqueous phase and acidic components in the oil phase which lead to generation of surfactants. This reaction makes the oil interface negatively charged which in turn makes the electrical repulsion forces between oil interface and the negatively charged solid surfaces. The process of wettability change is associated with redistribution of fluids at the pore scale by disjoining the previously wetting phase from solid interfaces and pushing it to the centre of the pores. Therefore, the speed of the process is partly dependent on the oil and the aqueous phase viscosities. In the case of heavy oil (especially the ones with very high viscosity) while accumulation of the in-situ generated surfactants at the oil interfaces is significantly higher than conventional oils which creates the electrical repulsion forces between the oil and rock, high viscosity of the heavy oil makes the process of wettability change (and fluid redistribution) towards more water-wet slow and time consuming. When the alkaline solution is injected at critical concentration of NaOH (the optimum pH and low IFT values) the effective period of chemical reaction between oil and injected solution is not more than 10 hours (for the conditions of our experiments) and after that the oil interface will be depleted from its surfactant components. While in this period the electrical repulsion forces between oil and rock interface are the highest, the time period is not sufficiently long to allow wettability change process take effect. We believe the inability of the injected AS solution to effectively alter wettability in our tests is due to the very high viscosity of the heavy crude oil and the short time scale of the chemical reaction between oil and AS solution.

A possible solution for enhancing wettability alteration process is to inject AS solution at lower concentrations in which the chemical reaction last longer. Injection of AS solution at lower concentration of alkaline may improve water-wetness of the system and consequently increase oil production by capillary cross-flow.

CONCLUSIONS

1. Injection of AS solution at the critical concentration of alkali (minimum IFT) significantly improved the rate and ultimate recovery of the extra-heavy oil.
2. A new capillary-driven recovery mechanism (capillary cross-flow) was recognized in the micromodel tests which was responsible for oil recovery from the high oil saturation regions (low permeability and connectivity areas) of the porous media towards the main flowing path of the AS solution (water channels) where the displaced oil was produced by emulsification mechanism.
3. The initial flow of the oil from uncontacted zones towards the main flowing path of AS solution is believed to be due to the existence of a zero (or very low) capillary pressure in the main flowing path of AS solution which creates a gradient across the porous medium.
4. The process of oil recovery by AS injection was observed to be very sensitive to the wettability state of the extra-heavy oil. Oil recovery process weakened as the system became less water-wet and almost stopped in the case of weakly and strongly oil-wet conditions.
5. For the extra heavy oil used in this study, injection of the AS solution at its critical concentration was unable to efficiently change the wettability of the oil-wet system toward water-wet conditions.

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Table 1: Dimensions of the micromodel and its pores.

Height	4 (cm)
Width	0.7 (cm)
Pv	0.01 (cm^3)
Ave. depth	50 (μm)
Pore Dia. Range	30-500 (μm)

Table 2: Basic properties of the extra-heavy crude oil used for the experiments.

API	11.5
Viscosity	8670 @ 50 °C
Asphaltene Content	11.6 (wt/wt%)
Acid Number	3.38 (mgKOH/gr)

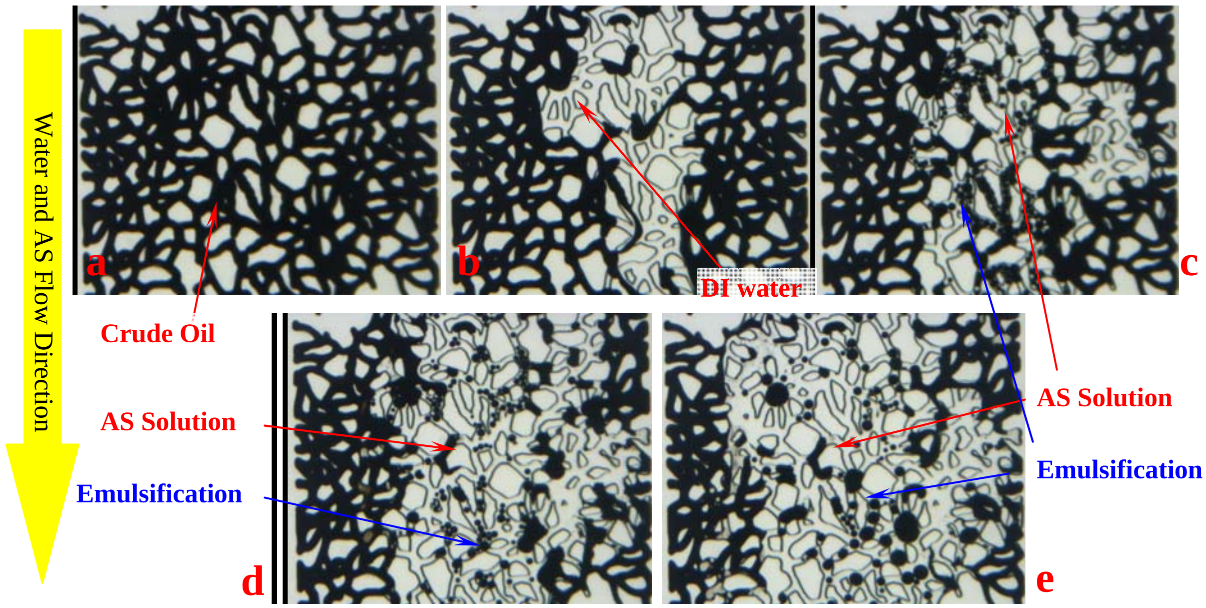

Figure 1: Fluid distribution in a magnified section of the homogeneous micromodel, after oil flood (a), waterflood (b), 2.5 hours of AS flood (c), 5 hours of AS flood (d) and, 10 hours of AS flood (e).

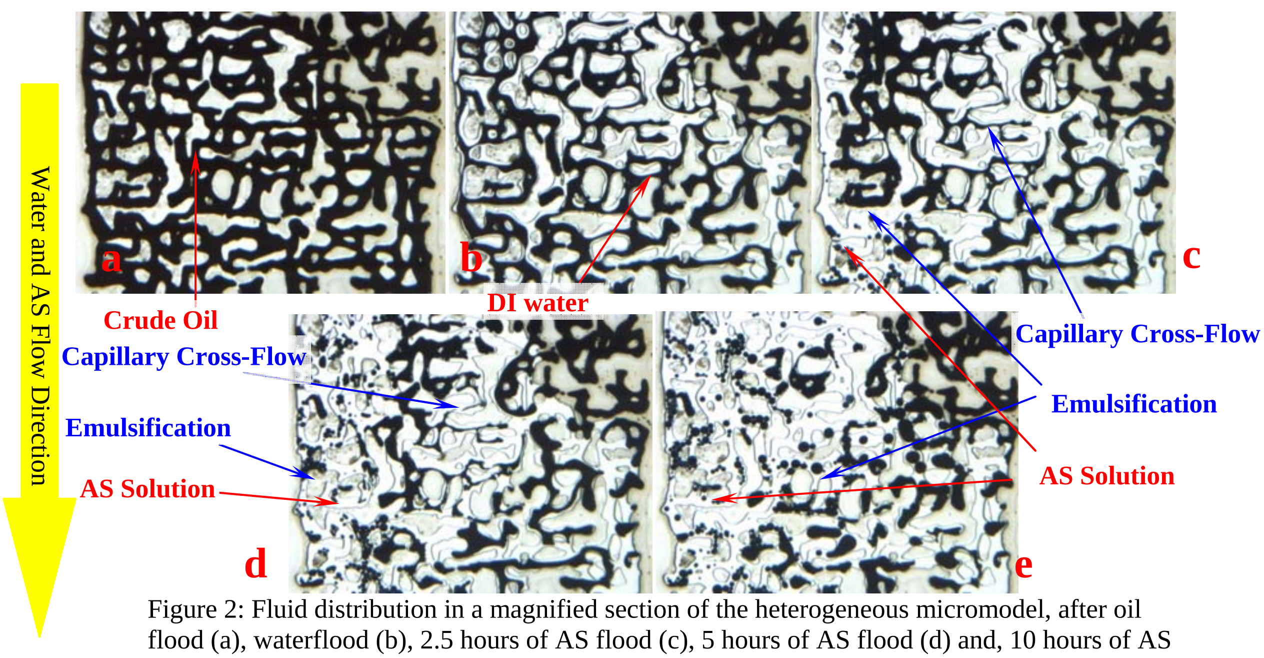

Figure 2: Fluid distribution in a magnified section of the heterogeneous micromodel, after oil flood (a), waterflood (b), 2.5 hours of AS flood (c), 5 hours of AS flood (d) and, 10 hours of AS flood (e).

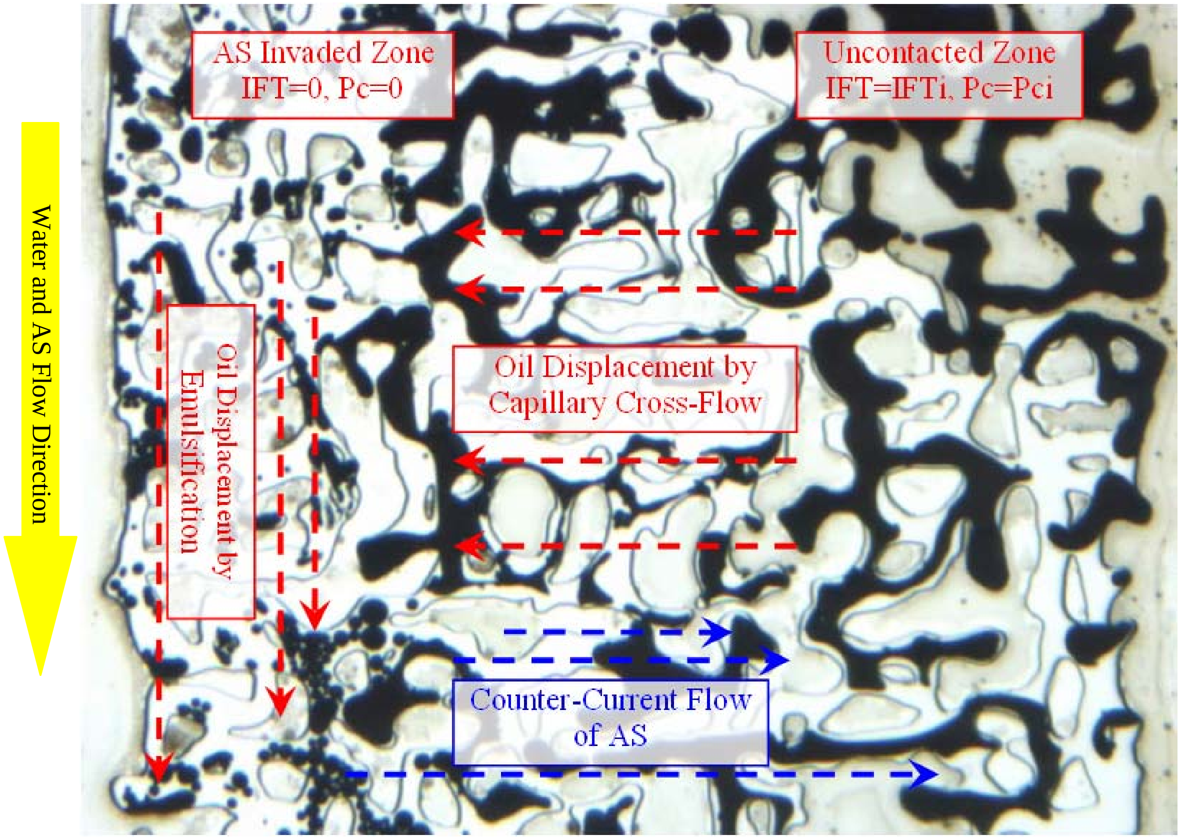

Figure 3: The effect of capillary cross-flow imbibition mechanism in oil recovery and effect of IFT reduction. The red arrows show the flow direction of the oil phase and the blue arrows show direction of counter-current flow of the AS solution. The yellow arrow on the left side of the picture shows flow direction of injected AS solution.

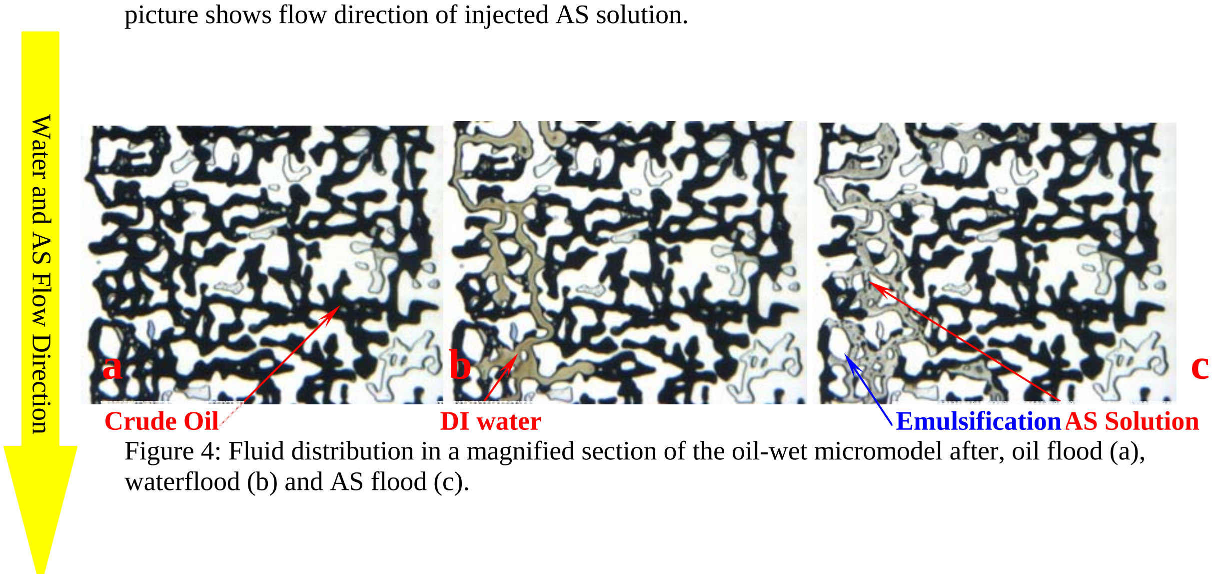

Figure 4: Fluid distribution in a magnified section of the oil-wet micromodel after, oil flood (a), waterflood (b) and AS flood (c).