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Mini-Review

Micromodel Studies of Surfactant Flooding for Enhanced Oil Recovery: A Review

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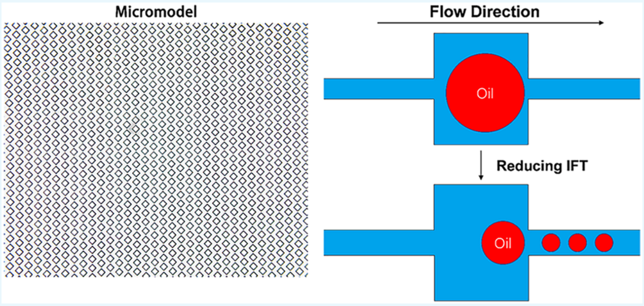
ABSTRACT: Micromodels have been widely used to visualize surfactant flooding, which provides new insights into understanding pore-scale events during displacement. In this review, recent advances in micromodel studies of surfactant flooding are briefly summarized. The mechanisms of surfactant flooding as demonstrated by micromodel studies are presented, as well as pore-scale findings that cannot be captured by traditional coreflood methods.



1. INTRODUCTION

Oil recovery is a process in which the oil flows in porous media to production wells driven by the reservoir pressure or pressure exerted by the displacing fluids. Water is the most widely used displacing fluid due to its accessibility and low cost. Despite the benefits of waterflooding, the oil recovery of waterflooding is low, resulting in a large amount of residual oil in the reservoir. The residual oil is mainly trapped by capillary pressure and cannot be recovered by further water injection. The addition of surfactant into the injected water can effectively reduce the oil−water interfacial tension (IFT), thereby making the trapped oil ganglia mobilized by the injected water.[1] Moreover, if the reservoir is oil-wet, the surfactant can change the wettability of the reservoir to water-wet so that the oil is released from the pore surface and can be recovered.[2] Therefore, surfactant flooding is an effective method for enhanced oil recovery (EOR) and its effectiveness has been confirmed by many field tests.[3]

Typically, surfactant flooding is conducted in cores or sandpacks to study its efficiency in improving oil recovery.[4] Although cores and sandpacks are good representatives of formations, the displacement cannot be visually observed, thus limiting the understanding of microscopic displacement mechanisms and phase distributions, which are important for optimizing surfactant flooding. Micromodels have been used for studying microscopic fluid flow in many applications.[5,6] The use of a micromodel makes it possible to observe the displacement at pore scale; thus the displacement mechanism and pore-scale events can be obtained.

The study of two-phase displacements in micromodels can provide insights into understanding macroscopic displacement dynamics. The displacement pattern map developed by Lenormand et al.[7] reveals the dependence of displacement patterns on capillary numbers and viscosity ratios by performing drainage in micromodels, which are widely used for the determination of displacement patterns. The subsequent micromodel study by Lenormand et al.[8] extended the displacement pattern map to imbibition.

Many micromodel studies of surfactant flooding have been conducted with the aim of revealing the displacement characteristics and mechanisms of surfactant flooding, such as IFT reduction, wettability alteration, emulsification, etc.[9−11] Some mechanisms of oil recovery by surfactant flooding have been verified by micromodel studies. Micromodel studies have also provided us with insights into surfactant flooding that have not been previously considered.

In this review, we focus on the recent advances in micromodel studies of surfactant flooding. The findings and mechanisms of surfactant flooding are summarized and discussed.

2. IFT REDUCTION

The reduction of oil/water IFT is considered to be the most important mechanism of surfactant flooding. The reduction of oil/water IFT by surfactants contributes to improve oil recovery in several ways. The reduction of IFT to low levels makes the trapped oil ganglia tend to be broken down into

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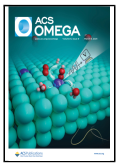


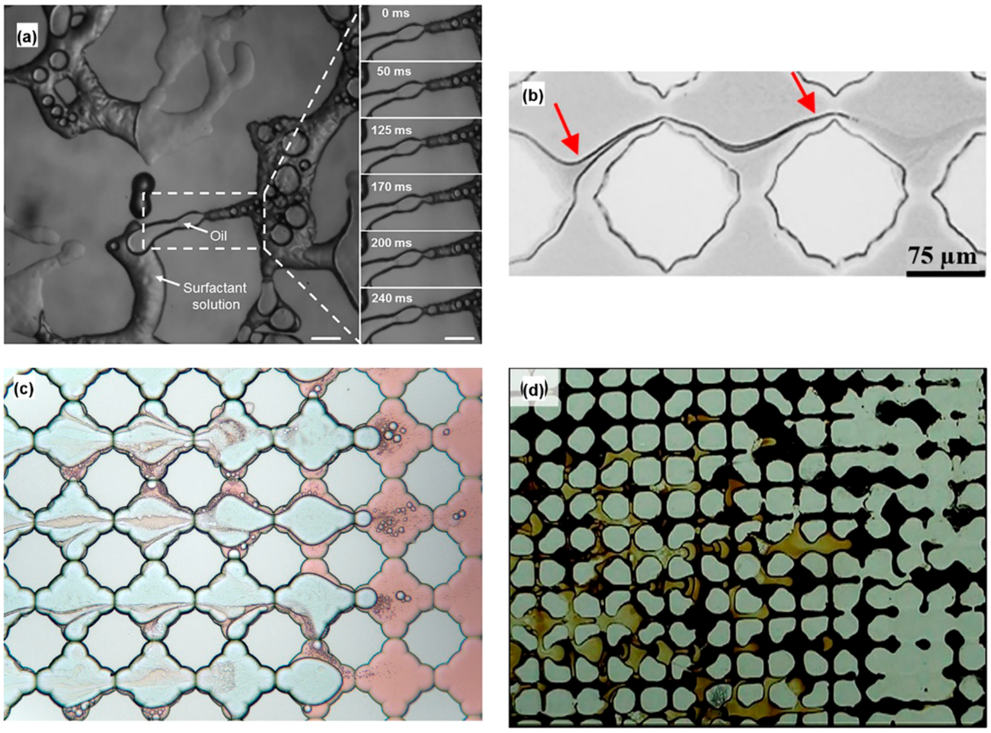


Figure 1. (a) Generation of O/W emulsions by snap-off at the pore throat during low IFT surfactant flooding [Reprinted with permission from ref 12. Copyright 2020 Elsevier]. (b) Residual oil becomes extremely flexible and can be elongated during ultralow IFT surfactant flooding [Reprinted with permission from ref 15. Copyright 2017 American Chemical Society]. (c) Significant increase of apparent contact angle during ultralow IFT surfactant flooding in water-wet micromodels [Reprinted with permission from ref 18. Copyright 2020 Society of Petroleum Engineers]. (d) Formation of W/O emulsions during ultralow IFT surfactant flooding due to the significant increase in dynamic contact angle [Reprinted with permission from ref 19. Copyright 2012 Elsevier].

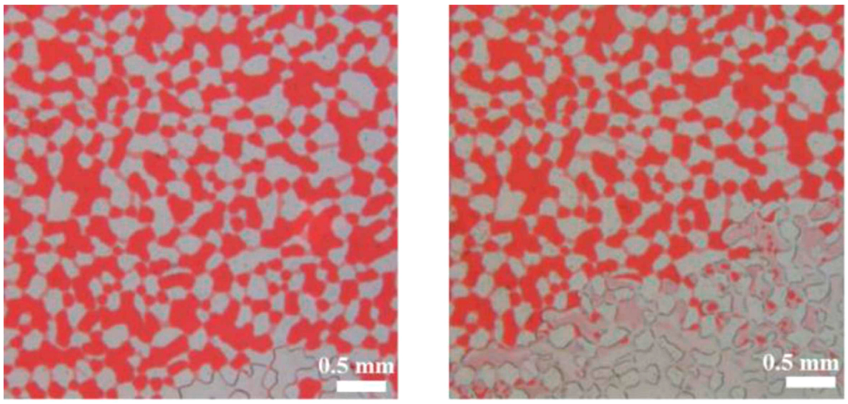
small oil droplets by snap-off at pore throats, which can much more easily pass through the pore throat and eventually be recovered (Figure 1a).[12,13] Moreover, the produced large oil droplets can block the water path and divert water to the unswept oil zone, thus improving the sweep efficiency and oil recovery. The further reduction of IFT to ultralow levels significantly improves the oil recovery.[14] Under the ultralow IFT, the trapped oil ganglia become extremely flexible and flow as rivulets with injected surfactant solutions (Figure 1b).[15,16] Therefore, at favorable viscosity ratios, the ultralow IFT surfactant flooding can substantially improve oil recovery.

Due to the fractured nature of carbonate reservoirs, the imposed flow occurs mainly in fractures and is difficult to enter the matrix. The oil recovery in a fractured reservoir by surfactant flooding is mainly dependent on the imbibition of surfactant solution into matrix. Studies show that imbibition of surfactant solutions into vertically positioned micromodels at ultralow IFT is driven by gravity, and a large amount of oil in the matrix can be recovered after a few days. For the horizontally positioned micromodels, since the gravity and capillary forces are negligible, the imbibition rate and oil recovery are both much lower, and the oil recovery is attributed to the solubilization of oil by micelles.[17]

A significant difference between surfactant flooding at low IFT and ultralow IFT is that the emulsification takes completely different approaches. Whether W/O or O/W emulsions are formed in porous media mainly depends on the contact angle, and the nonwetting phase tends to be discontinuous resulting in the formation of droplets.[12] The apparent contact angle during immiscible displacement in porous media is governed by the balance between capillary and viscous forces, and it increases with the increase of capillary number. For low IFT surfactant flooding in water-wet reservoirs, the capillary number is not high enough to significantly increase the advancing contact angle so that the oil remains the nonwetting phase, thus forming O/W emulsions (Figure 1a). For ultralow IFT surfactant flooding in water-wet reservoirs, the large capillary number makes the advancing contact angle greater than 90° (Figure 1c),[18] resulting in the formation of W/O emulsions rather than O/W emulsions during the displacement (Figure 1d).[19,20] The formation of viscous W/O emulsion during ultralow IFT surfactant flooding increases the pressure gradient and sweep efficiency, which effectively improve the heavy oil recovery.

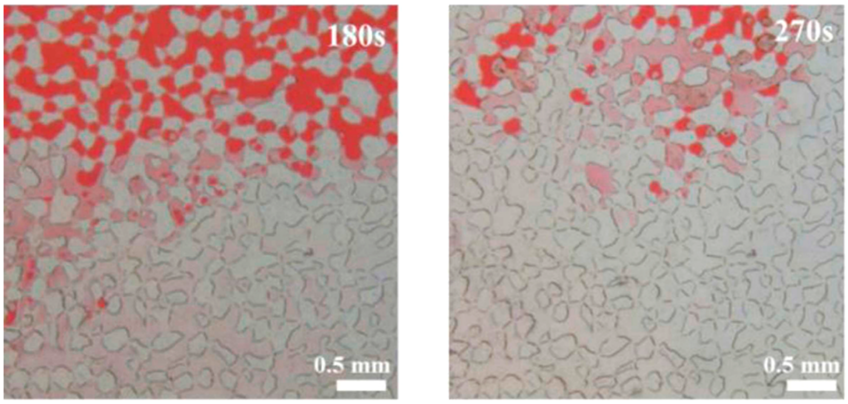
3. WETTABILITY ALTERATION

The surfactant-induced wettability alteration improves oil recovery in different aspects. In naturally fractured carbonate reservoirs, oil recovery from a tight matrix depends on spontaneous or forced imbibition, which is almost impossible if the matrix is strongly oil-wet at high IFT. The micromodel studies[21−23] indicate that the water cannot be imbibed into an oil-wet micromodel, whereas the type I microemulsion-forming surfactant solution can be spontaneously imbibed into the micromodel (Figure 2). The higher concentration of surfactant has a stronger ability to alter the wettability of micromodel toward being water-wet, which leads to a higher imbibition rate. However, the displacement becomes less stable as the surfactant concentration increases, and this is owing to the development of fingers at higher imbibition rates.[21] Therefore, both wettability alteration and invasion front stability should be considered to achieve a higher oil recovery. Micromodel



a: water 300s

b: Surfactant 30s



c: Surfactant 180s

d: Surfactant 270s

Figure 2. Water fails to effectively imbibe into the oil-wet micromodels after 300 s due to the hindrance by capillary forces. The type I microemulsion-forming surfactant solution can be spontaneously imbibed into the oil-wet micromodels because of the IFT reduction and wettability alteration [Reprinted with permission from ref 23. Copyright 2019 Elsevier].

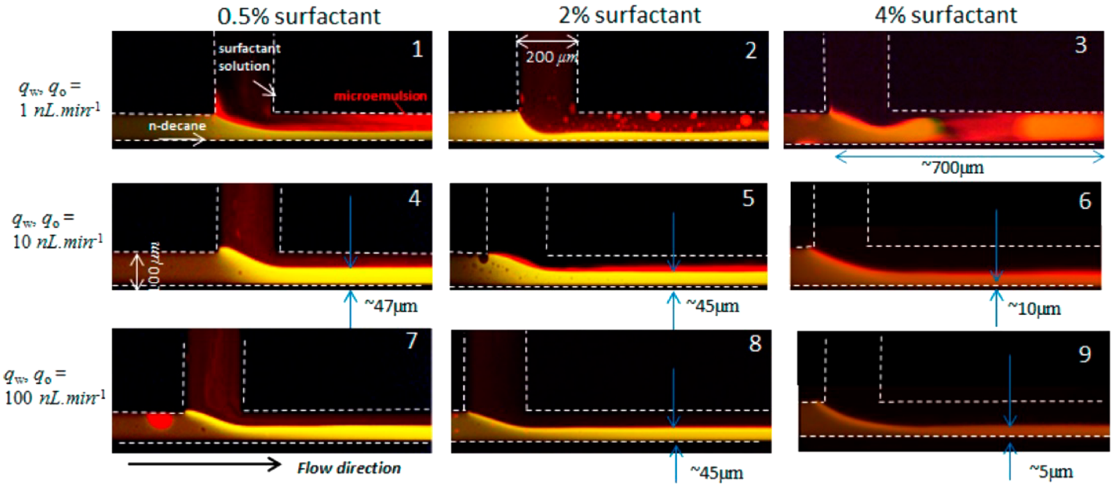


Figure 3. Flow dynamics and microemulsions formation at oil-surfactant solution interface at different flow rates and surfactant concentrations [Reprinted with permission from ref 6. Copyright 2016 American Chemical Society].

study[17] also shows that the reduction of IFT to ultralow levels can also effectively increase the imbibition rate under gravity. At ultralow IFTs, the capillary forces are dominated by gravity. Therefore, whether or not the wettability is altered has little effect on the imbibition rate.

The wettability alteration also contributes to the mobilization of residual oil, which plays an important role in EOR. In oil-wet reservoirs, the pore-scale displacement efficiency of waterflooding is low. The residual oil remains on pore surfaces and is difficult to remove because of the high detachment energy required. Surfactant can effectively change the wettability of micromodels from oil-wet to water-wet. The surfactant induced wettability alteration is time-dependent; with the change in wettability, the shape of residual oil changes from irregular to spherical (Figure 2c). After the wettability alteration is complete, the detachment energy is significantly reduced, thus making it easier to mobilize the residual oil. Moreover, the formation of microemulsions is competitive with the wettability alteration. As the salinity approaches the optimum value, the time required for wettability alteration is longer.[24]

Wettability is one of the most important factors determining oil—water displacement patterns in porous media. Experimental studies indicate that the displacement efficiency is low in strongly oil-wet micromodels, and the displacement efficiency is much higher in weakly water-wet or neutral micromodels.[25] Oil recovery can be effectively improved by surfactant flooding if the wettability of micromodels can be changed immediately after contact with the surfactant solution. However, as illustrated in Section 2, the significant increase of apparent contact angle during ultralow IFT displacements makes micromodels show oil-wet behavior, regardless of their wettability. Therefore, wettability alteration has little effect on the displacement patterns at ultralow IFT. Wettability alteration can significantly affect the displacement patterns at low and high IFTs, where the apparent contact angle is similar to the static contact angle.

4. MICROEMULSION FORMATION AND EFFECTS OF MICROEMULSIONS ON OIL RECOVERY

Microemulsions are thermodynamically stable mixtures of oil, water, and surfactant that form spontaneously during ultralow IFT surfactant flooding.[26] The formation of microemulsions during surfactant flooding will change the displacement dynamics. Meanwhile, the phase behavior of oil/water/surfactant system is usually determined under static and equilibrium conditions, and it needs to be revealed whether the microemulsions formed under flow conditions are similar to those formed under static conditions.

Experimental study[6] by coinjecting surfactant solution and oil into a micromodel with a T-junction shows that the microemulsions forms at the oil/surfactant solution interface (Figure 3). The formation of microemulsions is limited by diffusion. The surfactant solution and oil are gradually solubilized into the microemulsions, and the volume of microemulsion increases as the surfactant solution and oil flow from upstream to downstream. The formation of microemulsions during flow changes the flow patterns, and how the flow pattern is affected by microemulsions depends on the salinity and capillary numbers. During surfactant flooding, there is a lag in the formation of microemulsions, which are mainly formed from residual oil.[27,28] More microemulsions are formed as the displacement continues, leading to the formation of microemulsions bank, which can significantly change the displacement patterns in which the injected surfactant solution can become discontinuous. The type and solubilization ratio of microemulsions are typically determined by static phase behavior tests. The micromodel studies indicate that the microemulsions formed under dynamic conditions in micromodels are locally equilibrated, and the oil—water ratio of the microemulsions varies spatially due to changes in the surfactant solution composition during the displacement.[15]

The formation of microemulsions plays an important role in the recovery of residual oil.[24] For ultralow IFT surfactant flooding at unfavorable viscosity ratios, there is still a lot of unswept oil and trapped oil ganglia that can be recovered. The residual oil transforms into microemulsions when in continuous contact with a fresh surfactant solution. Although the IFT between surfactant solution and oil is ultralow, the IFT between surfactant solution and type III microemulsions can be even lower due to the nonequilibrium between the microemulsion and the surfactant solution. For a type I microemulsion-forming surfactant solution, the oil/surfactant solution IFT is higher than that of a type III microemulsion-forming surfactant solution. Type I microemulsions have an external phase of water and are therefore miscible with the injected surfactant solution as shown in Figure 2, making the residual oil completely solubilized. Therefore, more residual oil can be recovered by the formation of microemulsions during surfactant flooding. In addition, it has been observed that the microemulsions formed during surfactant flooding can destabilize into W/O emulsions, thereby blocking water channels and diverting water flow.[10]

5. CONCLUSIONS

We briefly reviewed recent advances in micromodel studies of surfactant flooding. The mechanisms of surfactant flooding and the displacement dynamics have been directly visualized by many studies. The reduction of IFT to low levels facilitates the transport and recovery of oil droplets, and the flow paths can be changed by blockage of pore throats by O/W emulsions. Oil recovery is significantly improved at ultralow IFT because the residual oil is more easily to be mobilized. Moreover, the dynamic contact angle increases as the IFT decreases, resulting in the formation of an O/W emulsions at low IFT while the emulsions formed at ultralow IFT become W/O. Forming either O/W emulsions or W/O emulsions has been shown to improve sweep efficiency. The wettability alteration by surfactants promotes the imbibition in the initially oil-wet micromodels. During surfactant flooding, more trapped oil droplets are mobilized due to wettability alteration. The formation of microemulsions during surfactant flooding can change the displacement patterns and increase the oil recovery by solubilizing the residual oil.

The existing micromodel studies of surfactant flooding mainly focused on revealing the pore-scale mechanisms of oil recovery. However, due to the complex phase behaviors of surfactant—water—oil system, the surfactant concentration (oil/water IFT) can vary spatially during the displacement. Therefore, how the displacement dynamics are affected is not fully understood. The goal of conducting pore-scale study is to provide new insights and guidelines for field applications. But how the pore-scale events affect core-scale and field-scale displacement parameters, such as relative permeability, has not been extensively studied and need to be investigated in depth in the future.

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The authors declare no competing financial interest.

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