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Investigation of gravity-stable surfactant floods

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HIGHLIGHTS

- A modified gravity stability theory was proposed for ultra-low IFT surfactant floods.
- Ultra-low IFT surfactant formulation was developed for the oil with favorable phase behavior and aqueous stability results.
- Surfactant floods were conduced and experimental results are in good agreement with proposed stability theory.
- A new approach was proposed for increasing the critical velocity by optimizing the microemulsion viscosity.

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ABSTRACT

Classical stability theory can be used to estimate the critical velocity of a miscible flood stabilized by gravity forces. However, stability theory for an ultra-low interfacial tension (IFT) surfactant displacement is not well developed or validated. In this paper, a method for predicting the critical velocity for a surfactant flood is proposed taking into account the microemulsion phase. Vertical upward surfactant displacement experiments were performed in sandpacks at velocities of 0.2, 0.4, 0.8 ft/day. The surfactant flood at 0.2 ft/day was a nearly stable displacement whereas the floods at 0.4 and 0.8 ft/day were unstable with visually obvious fingers. The stability theory is in good agreement with experimental results. The proposed theory and experimental results offer new insight into the behavior of surfactant floods stabilized by gravity forces and in particular the importance of the microemulsion phase and its properties, especially its viscosity. It is very important to measure the microemulsion viscosity and account for its effect on the critical velocity. Furthermore, the microemulsion viscosity can be optimized to improve the velocity for a stable displacement. This insight opens up a new pathway for optimizing surfactant floods without mobility control. It is possible to design an efficient surfactant flood without any mobility control if the surfactant solution is injected at a low velocity in horizontal wells at the bottom of the geological zone and the oil captured in horizontal wells at the top of the zone. This approach is practical if the vertical permeability of the geological zone is high. Under favorable reservoir conditions, gravity-stable surfactant floods may be an attractive alternative to surfactant–polymer floods.

1. Introduction

The hydrodynamic stability of both miscible and immiscible displacements in porous media has been studied for many years. Many investigators have reported both experimental and theoretical results for the effects of gravity and viscosity on the stability of miscible displacements [12,23,22,6,33,34,13,11,18] and immiscible displacements [7,5,36,30,9,28,20,24,10,31,19,21,29].

Surfactants can generate ultra-low IFT and displace almost all the residual oil after waterflooding a core (for recent experimental examples, see [38,2,1,3,4,27,17,32], but even at ultra-low IFT surfactant floods are still not miscible displacements [37]. The understanding of the gravitational stability of surfactant floods is lacking in the literature. Directly applying classical stability theory to ultra-low IFT surfactant floods is not appropriate and leads to inaccurate predictions. Thus, it is very important to understand the behavior of surfactant floods stabilized by gravity and propose a suitable theory for such applications.

In this paper, we propose a modified stability theory to calculate the critical velocity for ultra-low IFT surfactant floods taking into account the properties of the microemulsion. A series of surfactant displacement experiments were carried out to determine the critical velocity for a gravity-stable surfactant flood and these results were then compared with the proposed stability theory. The stability theory and experimental results imply that it is possible to design an efficient surfactant flood without any

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Nomenclature

g	gravitational acceleration constant
k	permeability
k_{ro}^0	endpoint oil relative permeability
k_{rw}^0	endpoint water relative permeability
k_{ro}	oil relative permeability
k_{rw}	water relative permeability
k_{rs}	surfactant solution relative permeability
k_{rme}	microemulsion relative permeability
M^0	endpoint mobility ratio
M_{OB}	oil bank/water mobility ratio
$M_{OB/me}$	oil bank/microemulsion mobility ratio
$M_{me/s}$	microemulsion/surfactant solution mobility ratio
v_c	critical interstitial velocity
v	interstitial velocity

Greek symbols

α	dip angle
μ_o	oil viscosity
μ_w	water viscosity
μ_s	surfactant solution viscosity
μ_{me}	microemulsion viscosity
λ_{ro}	oil relative mobility
λ_{rw}	water relative mobility
λ_{rme}	microemulsion relative mobility
λ_{OB}	oil bank mobility
ρ_o	oil density
ρ_w	water density
ρ_s	surfactant solution density
ρ_{me}	microemulsion density
ϕ	porosity

mobility control if the surfactant solution is injected at a stable velocity. A new approach is proposed for increasing the critical velocity by optimizing the microemulsion viscosity. The goal is to increase the rate at which a stable flood can be achieved.

There are many advantages to conducting a gravity-stable surfactant flood compared to a surfactant flood that uses polymer for mobility control. Polymers add to the cost, complexity and uncertainty of the process. Polymer stability over long time periods corresponding to reservoir floods is a concern at high temperature. Polymer transport is a concern in low permeability reservoirs when using high-molecular weight polymers. Gas can be injected with the surfactant solution to create an in situ foam for mobility control, but this process is much more complex and uncertain than using polymers for mobility control. Foam processes also require a source of high-pressure gas among other disadvantages. The common use of horizontal wells has made the design and operation of gravity-stable surfactant floods much more attractive. Such floods can be done at a higher velocity than possible with vertical wells in a dipping reservoir. The use of horizontal wells has other advantages as well such as higher volumetric sweep efficiency. Nevertheless, the velocity for a gravity-stable surfactant flood will still be too low for practical floods unless the vertical permeability is high. Furthermore, there cannot be any permeability barriers between the horizontal injector at the bottom of the zone and the horizontal producer at the top of the zone. However, optimizing the microemulsion viscosity as proposed in this paper for the first time will enable gravity-stable surfactant floods to be done at reasonable rates at a much lower permeability than previously thought possible.

2. Stability theory

Stability theory for water displacing oil in a homogeneous, uniform porous medium without a transition zone can be found in Lake [15]. The critical velocity is given by Eq. (1).

$$v_c = \frac{\Delta\rho g k k_{rw}^0}{\phi\mu_w(M^0 - 1)} \sin\ \alpha \tag{1}$$

where

$$\Delta\rho = \rho_w - \rho_o$$

and

$$M^0 = \frac{k_{rw}^0 \mu_o}{\mu_w k_{ro}^0}.$$

Now consider a vertical column of a homogeneous porous medium at residual oil saturation after waterflooding. An aqueous surfactant solution is injected from the bottom of the column at a constant velocity. Assume that only oil and aqueous phases flow through the porous medium. The aqueous phase containing surfactant displaces an oil bank (oil and water flowing together ahead of the surfactant), so when applying Eq. (1) the mobility ratio should be the mobility of the aqueous phase divided by the mobility of the oil bank. The total relative mobility of the oil bank is defined as the total mobility of the flowing oil and water phases at the saturations in the oil bank:

$$\lambda_{OB} = \lambda_{ro} + \lambda_{rw} = \frac{k_{ro}}{\mu_o} + \frac{k_{rw}}{\mu_w}$$

Eq. (1) is then changed to Eq. (2):

$$v = \frac{\Delta\rho g k k_{rw}^0}{\phi\mu_w(M_{OB} - 1)} \sin\ \alpha \tag{2}$$

where

$$M_{OB} = \frac{\lambda_{rw}}{\lambda_{OB}} = \frac{\frac{k_{rw}^0}{\mu_w}}{\frac{k_{ro}}{\mu_o} + \frac{k_{rw}}{\mu_w}}.$$

In reality, a microemulsion forms between the oil bank and the injected surfactant solution and should be taken into account since its density and viscosity are different than the water and oil. Assume a uniform microemulsion at its optimum salinity so the oil and water concentrations in the microemulsion are equal. Then the microemulsion density will be close to the average of the water and oil densities. For a light oil, the microemulsion viscosity at optimum salinity is typically about ten times larger than the oil viscosity. However, it should be measured under each specific condition since it varies over a wide range for different microemulsions. As illustrated in Fig. 1, there are four regions in the column: starting from the top and going down, there is water and oil at residual oil saturation (assuming the column has been water flooded to zero oil cut), oil bank with both oil and water flowing upward, microemulsion pushing the oil bank upward, and aqueous surfactant solution pushing the microemulsion upward. Eq. (3) can be applied at the interface between the microemulsion and oil bank as follows:

$$v = \frac{(\rho_{me} - \rho_o) g k k_{rme}}{\phi\mu_{me}(M_{OB/me} - 1)} \sin\ \alpha \tag{3}$$

where

$$M_{OB/me} = \frac{\lambda_{rme}}{\lambda_{OB}} = \frac{\frac{k_{rme}}{\mu_{me}}}{\frac{k_{ro}}{\mu_o} + \frac{k_{rw}}{\mu_w}}.$$