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Foam–oil interaction in porous media: Implications for foam assisted enhanced oil recovery

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ABSTRACT

The efficiency of a foam displacement process in enhanced oil recovery (EOR) depends largely on the stability of foam films in the presence of oil. Experimental studies have demonstrated the detrimental impact of oil on foam stability. This paper reviews the mechanisms and theories (disjoining pressure, coalescence and drainage, entering and spreading of oil, oil emulsification, pinch-off, etc.) suggested in the literature to explain the impact of oil on foam stability in the bulk and porous media. Moreover, we describe the existing approaches to foam modeling in porous media and the ways these models describe the oil effect on foam propagation in porous media.

Further, we present various ideas on an improvement of foam stability and longevity in the presence of oil. The outstanding questions regarding foam–oil interactions and modeling of these interactions are pointed out.

Contents

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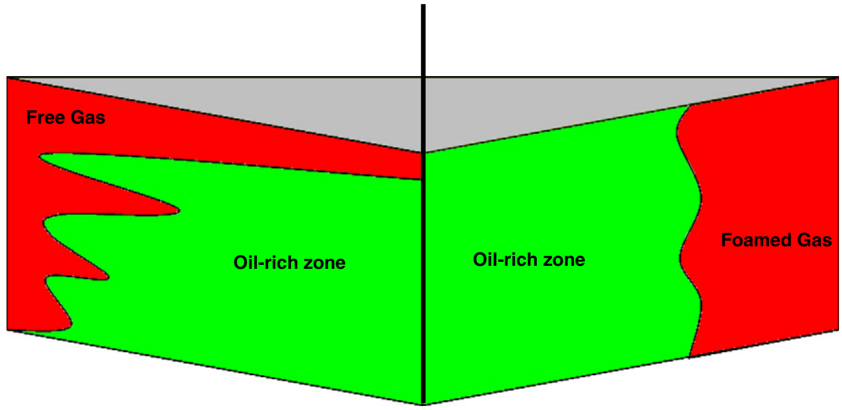

Fig. 1. Schematic of gas flooding vs. foam flooding: foaming of the gas modifies its profile by lowering gas mobility.

1. Introduction

The initial pressure of a hydrocarbon reservoir is sufficient to produce only a small fraction of the initial hydrocarbon in place at the end of the natural depletion stage. A common practice in the petroleum industry is then to inject water or other fluids into the underground formation to extract the hydrocarbon contained in small pores, that is to apply improved/enhanced oil recovery (IOR/EOR) methods [1,2]. Carbon dioxide (CO_2), nitrogen (N_2), air and hydrocarbon gasses (mainly methane) are commonly used in gas enhanced oil recovery (EOR) [3–7]. The main advantage of gas is its better microscopic sweep leading to lower residual oil saturation (fraction of oil in the pore space) in the pores compared to waterflood [1]. The major challenge associated with gas injection is its poor volumetric sweep efficiency, as the result of which gas does not contact a large fraction of oil and, thus, the overall recovery remains low [8,9] (see Fig. 1). This happens because of the channeling (flow of gas in the high permeability streaks in heterogeneous reservoirs), viscous fingering that occurs because of the viscosity difference between the oil and gas, and gravity override due to the large density contrast between the gas and oil [10–13]. In permeable media, the flux of a given phase is the product of a pressure gradient and the *mobility* of that phase [1]; gas mobility is much greater than that of oil or water primarily because its viscosity is so much smaller, which leads to fingering and makes channeling worse.

Foaming of the injected gas is a potential solution for the above-mentioned challenges in gas EOR method [14–21]. Foam can also be used to support thermal (e.g. steam) [22–25] or chemical (e.g. alkaline-surfactant-polymer) EOR [26–28]. Foam in porous media is a gas/liquid mixture with a continuous liquid phase (containing the surfactant) wetting the rock whereas a part or all of the gas is made discontinuous by thin liquid films called lamellae [22,29]. Thus, the foam is made by adding a surfactant solution to a gas injection. There are two main methods to obtain the foam in porous media. These include co-injection of gas and liquid, and surfactant alternating gas (SAG) injection. In the first strategy the gas and liquid are co-injected at a fixed ratio. The ratio between the gas flowrate, q_g, and the sum of the gas and the liquid flowrates (total flowrate, q_g+q_{liq}) determines the foam quality. Thus, the foam quality, f_g, is defined as:

$$f_g = \frac{q_g}{q_g + q_{liq}}. \quad (1)$$

In SAG injection, a surfactant solution and gas are injected in alternating slugs [18,21,30,31]. If the slugs are small, they mix near the well and (if gravity segregation has not occurred) at a sufficiently large radius approximate injection at a fixed foam quality. The reduction in gas mobility is greater for the co-injection foam than for the SAG foam with the same gas flowrate [32]. In addition to co-injection and SAG, it is possible to dissolve a foaming surfactant into supercritical CO_2 [33]. In this case, when “gas” meets water in the reservoir foam is formed, and no liquid slug need be injected.

When the foam films are created in porous media the flow of gas is largely hindered [17]. Subsequently, the injected gas can reach the

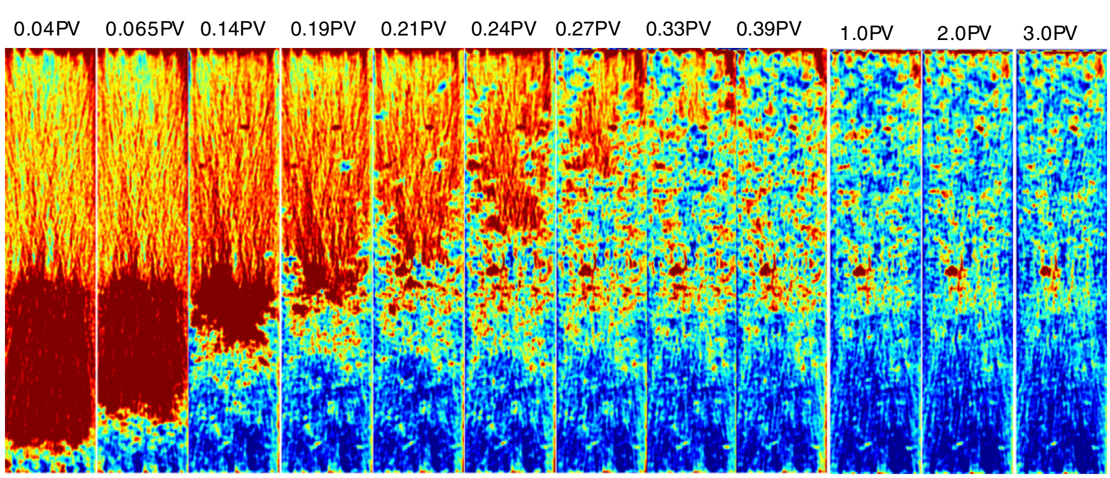

Fig. 2. CT images of N_2 foam flow (blue, gas and surfactant solution) in the Bentheim core initially saturated with surfactant solution (red) and water-flood residual oil (orange, surfactant solution and oil) at $P=1$ bar and $T=20$ °C. Gas is injected from the bottom. The time of each image is shown in pore volumes of the injected gas. The green part after 0.2 PV constitutes the region where there are three phases [35].