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Effect of temperature on foam flow in porous media

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ABSTRACT

Foam can increase sweep efficiency within a porous medium, which is useful for oil-recovery processes [1]. The flow of foam in porous media is a complex process that depends on properties like permeability, porosity and surface chemistry, but also temperature. Although the surface activity of surfactants as a function of temperature is well described at the liquid/liquid or liquid/gas interface, data on the effect of temperature on foam stability is limited, especially in porous media.

In this work, we tested a surfactant (AOS) at different temperatures, from 20 °C to 80 °C, in a sandstone porous medium with co-injection of foam. The pressure gradient, or equivalently the apparent viscosity, was measured in steady-state experiments. The core-flood experiments showed that the apparent viscosity of the foam decreased by 50% when the temperature increased to 80 °C. This effect correlates with the lower surface tension at higher temperatures. These results are compared to bulk foam experiments, which show that at elevated temperatures foam decays and coalesces faster. This effect, however, can be attributed to the faster drainage at high temperature, as a response to the reduction in liquid viscosity, and greater film permeability leading to faster coarsening.

Our results using the STARS foam model show that one cannot fit foam-model parameters to data at one temperature and apply the model at other temperatures, even if one accounts for the change in fluid properties (surface tension and liquid viscosity) with temperature. Experiments show an increase in gas mobility in the low-quality foam regime with increasing temperature that is inversely proportional to the decrease in gas-water surface tension. In the high-quality regime, results suggest that the water saturation at which foam collapses fmdry increases and P_c^* decreases with increasing temperature.

Introduction

Foam is a dispersion of gas bubbles in a continuous liquid medium where bubbles are separated by thin films called lamellae. Foam for Enhanced Oil Recovery (EOR) aims at controlling gas mobility and dealing with phenomena such as gas gravity override, viscous fingering and preferential channeling due to reservoir heterogeneity [2–4]. Despite the fact that active research on foam for EOR has been on the rise, relatively few field or pilot applications have been developed. In the field, foam can be injected by co-injection of gas and surfactant or by surfactant-alternating-gas (SAG) injection. SAG injection with large slugs of liquid and gas injected at the maximum allowable pressure is the preferred approach for field injection to minimize gravity override and time of injection [5].

Bulk foam experiments present foam which is not in contact with the rock, and generally in a tube. Although there is no consensus on the link between bulk and core-floods tests, bulk foam experiments can serve to evaluate foam stability with respect to oil and surfactant type and concentration [6,7], gas composition [8] or temperature. Maini et al. [9] showed that the half-life for foam volume decay in a tube declined dramatically with increasing temperature; sulfonates were found to be clearly superior, and in particular the relative performance of long-chain alpha olefin sulfonates improved with increasing temperature. In their study, Sharma et al. [10] found that the surface tension and bubble size decreased as the temperature increased. With increasing temperature, initial foam volume increased whereas foam half-life (or foam stability) decreased; the difference was more pronounced in the range 20 to 40 °C than between 40 and 80 °C. The foam film

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Nomenclature

SI units are assumed for all parameters used in calculations.

epcap	foam parameter controlling shear thinning
epdry	foam parameter controlling abruptness of foam collapse
fmcap	foam parameter assumed equal to smallest expected capillary number
fmmob	reference mobility reduction factor
fmdty	critical water saturation at which foam collapses
FI	foaming index
MRF	mobility reduction factor
k_{rg}	relative permeability of gaseous phase in absence of foam
k^{o}_{rg}	end-point relative permeability of gaseous phase
k_{rw}	relative permeability of aqueous phase
k^{0}_{rg}	end-point relative permeability of aqueous phase
N_{ca}	capillary number
n_g	exponent in k_{rg} curve
n_w	exponent in k_{rw} curve
S_{gr}	residual gas saturation
S_w	water saturation
S_{wc}	connate water saturation
t	time (s)
u	darcy velocity (ft./day)
V	volume (mL)
ε	liquid fraction
φ	porosity
μ_g	viscosity of gas (cP)
μ_w	viscosity of water (cP)
μ_{app}	average apparent foam viscosity for middle core section (cP)
σ_{wg}	surface tension (mN/m)

permeability, which is a measure of foam stability, increases with increasing temperature [11]. Foam behavior within a porous medium at reservoir conditions can significantly vary from the bulk experiments, particularly under different thermodynamic conditions [12].

Laboratory core-floods represent a more realistic prediction tool for foam EOR and can serve to quantify foam-model parameters [13]. SAG core-floods can be difficult to interpret because of uncertainties they can introduce: slow foam dynamics in the laboratory due to slow foam generation can introduce significant bias in the results, since local-equilibrium conditions do not apply [14]. Moreover, averaging pressure gradients (or, equivalently, apparent viscosity) throughout the entire core length can introduce bias as separate segments of the core exist at different states; an entrance region can exist where foam never reaches its full strength, and also a capillary end effect can be present at the core outlet controlling liquid saturation which, in turn, influences foam behavior [15].

Steady state co-injection core-floods can be divided in two main categories: (a) constant velocity foam scans, which obtain data at a fixed total superficial velocity while varying gas and liquid superficial velocities [16,17], and (b) experiments which scan the whole liquid velocity vs. gas velocity map. In the latter case the aim is to identify two regimes. In the so-called "low quality" regime the pressure drop is independent of liquid velocity, and in the "high quality" regime the pressure drop is independent of gas velocity. These experiments are time-consuming and relatively few in the literature; examples of the two regimes are found in the studies [18,19]. The two regimes are reflected also in the constant-velocity foam scans (option (a) above), which was the experimental method chosen for this study.

In modeling foam, Implicit Texture (IT) models are used in most commercial simulators, e.g. STARS (2007) [20]. These models represent the effects of bubble size implicitly through parameters that regulate gas mobility as a function of phase saturations pressure gradient and other factors. These models assume that local steady state is attained instantaneously everywhere in the porous medium. For the purpose of this work only IT models are described and used. They model the effect of foam on mobility by applying a mobility reduction factor (MRF) to the gas relative permeability (or equivalently by increasing gas apparent viscosity). The MRF is a product of different factors/functions which account for the effect of different processes that affect foam behavior, e.g. the presence of oil, surfactant concentration, water saturation or non-Newtonian shear effects (see Appendix A). These functions include a number of parameters. The modeling methods of Boeije and Rossen [21] and Ma et al. [16] have been developed to derive values for some of such parameters by fitting models to the constant velocity foam scan experimental datasets.

This paper investigates the effect of temperature on foam in oil-free core-floods, as well as on bulk foam. The testing hypothesis is that as temperature changes, several effects can take place concurrently which can influence foam performance: modification of interfacial rheology, gas–liquid surface tension, and changes in liquid viscosity are expected to influence foam behavior. For the systems studied, we correlate foam behavior in the core-floods with bulk experimental results.

Methods

The bulk foam experiments were carried out at four different temperatures. The experiment was conducted in a Foamscan apparatus (Teclis instruments), a tube with 3 cm inside diameter with a double wall coupled with a circulating bath controlling the temperature in the column. The surfactant solution was Alpha Olefin Sulfonate (AOS, Bio-Terge 14-16C, Stepan Chemical Co.) 14-16C at 1% active concentration in a 1%w/w NaCl (Merck) solution. The foam was created by sparging gas though a porous glass frit (3 mm thickness with pores size in the range of 100–160 μm)) into 50 ml of surfactant solution which created foam in the tube. During foam generation the gas was injected at a fixed rate of 50 ml/min (standard conditions) and stopped automatically when the foam volume reached 200 ml. Then the liquid fraction in the foam and the foam volume were monitored.

A pair of electrodes at the bottom of the column, immersed in the liquid, measures the drained liquid volume below the foam. The total volume (foam + liquid) was measured with a camera and the volume of the foam at any time was calculated by subtracting the liquid volume from the total volume. Another pair of electrodes were located above the liquid level to measure the liquid fraction in the foam. The electrodes were calibrated with the surfactant solution at the targeted temperature. A temperature sensor inside the tube allowed the measurement of the temperature there.

Surface tension measurements were performed using an EZ-Piplus tensiometer (Kibron Inc.) employing a Du Noüy ring with a microsize probe of 0.51 mm diameter. The instrument was connected to a circulating bath to control the temperature. Once the instrument reached the targeted temperature, the surfactant solution was maintained at that temperature for 30 min before starting the measurements. The surface tension was measured using the Du Noüy method with a microsize probe of 0.51 mm diameter.