Effect of surfactant concentration on foam: From coreflood experiments to implicit-texture foam-model parameters

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A B S T R A C T

We present a comparative study of foam coreflood experiments with various surfactant concentrations. Plots of apparent viscosity vs. injected gas fraction were obtained for surfactant concentrations at the critical micelle concentration and above. Bulk foam stability was measured for all concentrations and compared with the coreflood results. There were different responses to surfactant concentration in bulk and in corefloods.

The coreflood results were matched with an implicit-texture foam model, and the dependency of the model parameters on the surfactant concentration is discussed. Fitting the data requires relating the surfactant concentration to the dry-out function or the limiting capillary pressure.

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Introduction

Foam is a dispersion of gas bubbles in a continuous liquid phase where bubbles are separated by thin liquid films called lamellae, stabilized by surfactants or nanoparticles [1–3]. 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 [4,5]. 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 its 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 [6].

Surfactant molecules stabilize the liquid films separating the foam bubbles. It is crucial to select the correct surfactant and the correct surfactant concentration, so as to stabilize the foam in an EOR process. Foam stability is generally investigated with bulk foam and coreflood experiments. When considering the effect of surfactant concentration, there is a large body of work on the effect on bulk foam stability, e.g. [7], however there is significantly less information on the effect of surfactant concentration on behavior in corefloods. Aronson et al. [8] studied the disjoining pressure isotherms for two surfactant concentrations and found that the higher concentration gave a higher disjoining pressure. The solution with higher disjoining pressure, which is indicative of higher limiting capillary pressure, gave foams that had large flow resistance, i.e. gave large pressure gradients along the core. Apaydin and Kovscek [9] considered transient flow behavior and gas mobility at a fixed foam quality and found that displacement efficiency decreased and gas mobility increased (i.e. the foam became weaker) with decreasing surfactant concentration. They linked this behavior to the limiting capillary pressure, related to the maximum capillary pressure a foam film can withstand, which is higher at higher surfactant concentrations. Farajzadeh et al. [10] also reported that higher surfactant concentrations gave higher values of the limiting capillary pressure. Alvarez et al. [11] found that the changes in the limiting capillary pressure with surfactant concentration caused changes in the foam quality at which the transition from low quality to high quality (coalescence dominated) foam behavior occurred, i.e. higher surfactant concentrations gave foams that were stable to higher foam qualities. Schramm and Green [12] considered the Marangoni surface elasticities for a range of different surfactant concentrations. They showed surface elasticity decreased with increasing surfactant concentration. In parallel, they showed that

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Nomenclature

SI units are assumed for all parameters used in calculations.

A	cross-sectional area of core sample
c	surfactant concentration
C_{surf}	surfactant concentration for the IT model
epcap	foam parameter controlling shear thinning
epdry	foam parameter controlling abruptness of foam collapse with respect to water saturation
epsurf	foam parameter controlling abruptness of foam collapse with respect to surfactant concentration
F_1	function of surfactant concentration C_{surf} on foam properties
F_2	function of water saturation on foam properties
F_3	function of oil saturation
F_4	function of gas velocity
F_5	function of capillary number
F_6	function of critical capillary number
FM	mobility reduction factor
fmcap	foam parameter assumed equal to smallest expected capillary number
fmmob	reference mobility reduction factor
fmdry	critical water saturation at which foam collapses
fmsurf	critical surfactant concentration below which the foam collapse
f_g	gas fraction or foam quality
f_g^*	transition foam quality
k	measured permeability of rock sample to surfactant solution
k_{rg}	relative permeability of gaseous phase in the absence of foam
k_{rg}^0	end-point relative permeability of gaseous phase
k_{rw}^0	end-point relative permeability of aqueous phase
N_{ca}	capillary number
n_b	number of bubbles
n_g	exponent in k_{rg} curve
n_w	exponent in k_{rw} curve
P_c^*	limiting capillary pressure
q_t	total volumetric flow rate
q_{gas}	gas volumetric flow rate
q_{liq}	liquid volumetric flow rate
r	radius of the bubble
S_b	total surface area of bubbles
S_{gr}	residual gas saturation
S_w	water saturation
S_w^*	water saturation at P_c^*
S_{wc}	connate water saturation
u	Darcy velocity
V_s	volume of surfactant solution
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)

decreasing surface elasticity gave increased mobility reduction. This suggests that increasing surfactant concentration will increase mobility reduction.

Bulk foam experiments are performed in general by sparging gas in a surfactant solution which is not in contact with rock. Although there is no consensus on the link between bulk and coreflood tests, bulk foam experiments can serve to evaluate foam stability with respect to oil and surfactant type [13–15], gas composition [16] or temperature [17]. The half-life for foam volume decay in a tube declines dramatically with surfactant concentration below the critical micellar concentration (CMC) [18]. The CMC is defined as the surfactant concentration above which the surface tension remains constant. DLVO models [19,20] provide a phenomenological explanation of foam film stability based on the disjoining pressure. Scheludko and coworkers [21] proposed that the film will be destabilized when the capillary pressure, P_c, is greater than the structural disjoining pressure. The critical disjoining pressure above which foam films break is believed to be a function of surfactant type and concentration, and electrolyte concentration [1]. Khatib et al. [22] showed that foam-film stability was related to gas mobility reduction. They observed that foam dramatically coalesces at a specific capillary pressure, called the "limiting capillary pressure", P_c^*, above which foam is unstable. Below P_c^*, the foam coalescence decreases and, consequently, foam apparent viscosity increases. The limiting capillary pressure varies with surfactant type and concentration, electrolyte concentration, foam flowrate and porous medium permeability. Aronson et al. [8] studied the relation between the "critical" and "limiting" capillary pressures by measuring the disjoining pressure isotherms of the sodium dodecyl sulfate (SDS) solution and the pressure drop obtained by injecting the same solution in a sandpack. Their results showed that the solutions with highest disjoining pressure display the highest pressure drop in the porous medium and thus the largest flow resistance. Moreover, they found that the "limiting" capillary pressure for foam coalescence in porous media is close to the rupture pressure of a single foam film.

Steady-state co-injection corefloods can be performed by measuring the pressure drop across the core, maintaining constant total superficial velocity while varying gas and liquid fractional flow [23,24]. This "foam scan" experimental method was chosen for this study. Two regimes can be identified: the "low-quality" regime, "quality" referring to gas fractional flow, in which the pressure drop increases with the increase of the gas fraction, and in the "high-quality" regime, in which the pressure drop decreases with the increase of gas fraction. In between these two regimes, the pressure drop generally reaches a single maximum value.

In modeling foam, implicit-texture (IT) models are used in commercial simulators, e.g. STARS [25], which assume that local steady state is attained instantaneously everywhere in the porous medium [10]. For the purpose of this work, only IT models are described and used. Foam mobility is modeled by applying a mobility reduction factor (FM) to the gas relative permeability (or equivalently by increasing gas apparent viscosity—defined below). The FM factor is a product of different functions which account for the effect of different mechanisms that affect foam behavior, e.g. the presence of oil (saturation and composition), surfactant concentration, water saturation and/or non-Newtonian shear effects (see Appendix B). These functions include a number of parameters. The modeling methods of Boeije and Rossen [26] and a modified version [10,17] of the Ma et al. [27] method have been employed to derive values for some of these parameters by fitting the models to the constant total velocity foam-scan experimental datasets.

This paper investigates the effect of surfactant concentration on foam in oil-free corefloods, over a wide range of concentrations, from the CMC up to concentrations similar to those used in corefloods, and across the whole range of foam qualities at