Mechanistic Studies of Improved Foam EOR Processes

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DISCLAIMER

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ABSTRACT

The objective of this research is to widen the application of foam to enhanced oil recovery (EOR) by investigating fundamental mechanisms of foams in porous media. This research will lay the groundwork for more applied research on foams for improved sweep efficiency in miscible gas, steam and surfactant-based EOR. Task 1 investigates the pore-scale interactions between foam bubbles and polymer molecules. Task 2 examines the mechanisms of gas trapping, and interaction between gas trapping and foam effectiveness. Task 3 investigates mechanisms of foam generation in porous media.

The most significant progress during this period was made on Tasks 1 and 3.

Research on Task 1 focused on selecting and characterizing a surfactant/polymer formulation for initial experiments. The two (high-quality and low-quality) strong-foam regimes were identified from steady-state coreflood data for the formulation without polymer, for comparison with behavior with polymer. This formulation showed unconventional behavior in the low-quality regime in that pressure gradient decreases at increasing liquid injection rate. Such behavior was not seen in most previous studies of foam, but it is consistent with dense-CO_2 foam data recently obtained in our laboratory. We are considering the significance of the unconventional trend in the data and proceeding with initial experiments with polymer.

Research on Task 3 focused on foam generation at limited pressure gradient in sandpacks. In these experiments liquid injection rate and pressure drop across the core are held fixed, and gas injection rate responds to creation and properties of foam. Initial experiments included three permeabilities (1.2, 3.6 and 5 darcy), three surfactant concentrations (0.12, 1.2 and 2.4 wt%) and two liquid injection rates (1.29 and 2.76 ft/day). Separating experimental artifacts from physical phenomena in these experiments is difficult and an ongoing process.

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OBJECTIVES

The objective of this research is to widen the application of foam to enhanced oil recovery (EOR) by investigating fundamental mechanisms of foams in porous media. This research will lay the groundwork for more applied research on foams for improved sweep efficiency in miscible gas, steam and surfactant-based EOR. Task 1 investigates the pore-scale interactions between foam bubbles and polymer molecules. Task 2 examines the mechanisms of gas trapping, and interaction between gas trapping and foam effectiveness. Task 3 investigates mechanisms of foam generation in porous media.

EXPERIMENTAL

The experimental techniques employed vary with the specific task addressed. Therefore the experimental techniques are discussed together with the Results and Discussion section on each task, below.

RESULTS AND DISCUSSION

TASK 1: INTERACTIONS BETWEEN POLYMER AND FOAM

This work is motivated by a hypothesis about how polymer interacts with foam in porous media. The hypothesis derives in turn from the observation that steady-state foam behavior appears to comprise two very different flow regimes, at high and low foam qualities (injected gas volume fraction) (Figure 1) (Alvarez *et al*., 2001). The high-quality regime is controlled by lamella stability, while in the low-quality regime foam lamellae are relatively stable, bubble size is fixed, and behavior is controlled by gas trapping and mobilization. In the high-quality regime, water saturation S_w is held nearly constant at the water saturation S_w^* corresponding to the "limiting capillary pressure" (Khatib *et al*., 1988; Rossen and Zhou, 1995). In the high-quality regime, applying Darcy's law to the aqueous phase at fixed water saturation S_w^* gives

$$\nabla p = u_w \mu_w / (k\, k_{rw}(S_w^*)) \qquad (1)$$

where u_w is water superficial velocity, μ_w is aqueous-phase viscosity, k is permeability and $k_{rw}(S_w^*)$ the relative permeability to the aqueous phase at S_w^*. Our hypothesis is that polymer affects foam in the high-quality regime by (a) viscosifying the aqueous phase (increasing μ_w) and (b) stabilizing or destabilizing foam lamellae (reducing or increasing S_w^*, respectively). One can distinguish between these effects by measuring the viscosity of the aqueous phase separately from the foam (accounting if possible for the effects of shear rate on polymer viscosity). If upon addition of polymer the pressure gradient in porous media in the high-quality regime increases more than does μ_w, then polymer stabilizes foam lamellae; if pressure gradient increases less than does μ_w, then polymer destabilizes the lamellae.

During this period we began constructing our apparatus, selecting surfactants and polymers for use in experiments, and quantifying polymer rheology in the absence of foam. For comparison with previous work, we selected 0.1 wt % of a relatively lowmolecular weight (500,000) polyacrylamide for initial study. The surfactant is a 1 wt % solution of alpha olefin sulfonate in 0.1 wt % Na^+, 0.05 wt % Ca^{++}. This polymer adds little to the viscosity of the aqueous phase at this salinity, so the effects of polymer on foam stability would be most easily distinguished.

We have determined the two steady-state strong-foam regimes for the surfactant formulation without polymer (Figure 2). In the high-quality regime, ∇p is nearly independent of gas injection rate, as expected. In the low-quality regime, however, pressure gradient decreases at increasing liquid injection rate, holding gas injection rate constant. Similar behavior is seen with polymer in the study of Romero *et al.* (2002), but the only examples we know of without polymer are the studies of Dong (2001) and ongoing M.S. research of Kim in our laboratory, both with dense-CO_2 foam. Such a trend is consistent with the foam-viscosity model of Hirasaki and Lawson (1985), where effective gas viscosity decreases with increasing liquid injection rate; but that presupposes that (a) bubble size is not changing and (b) gas trapping is held constant in our experiment as in their theory. Such a trend is also consistent with the model and data of de Vries and Wit (1990). We are investigating the significance of this behavior.

We have begun experiments with polymer. Early results indicate that foam generation with polymer requires higher injection rates of gas and liquid than without polymer. This suggests that the foams are less stable with polymer than without.

TASK 2: GAS TRAPPING

There were no significant advances in this task during this period.

TASK 3: FOAM GENERATION

We have begun experiments examining foam generation with limited pressure gradient, following up on earlier research showing a minimum pressure gradient for foam generation and an unstable regime at intermediate pressure gradients (Figure 3) (Gauglitz *et al.*, 2002; Kam and Rossen, 2002). Our initial experiments will be conducted in sandpacks; the same trends in foam behavior are observed in sandpacks as in consolidated core, but at lower pressure gradient (Khatib *et al.*, 1988; Alvarez *et al.*, 2001; Gauglitz *et al.*, 2002). It is much more convenient to work in sandpacks than consolidated core, because at low pressure drop in a sandpack one does not need to apply back-pressure. Fluctuations in back-pressure are hard to completely eliminate, and they can introduce transient false pressure gradients into the apparatus, which can in turn trigger foam generation.

Initial experiments included three permeabilities (1.2, 3.6 and 5 darcy), three surfactant conentrations (0.12, 1.2 and 2.4 wt%) and two liquid injection rates (1.29 and 2.76 ft/day). Separating experimental artifacts from physical phenomena in these experiments is difficult and an ongoing process. One early result of the new effort is shown in Figure 4. In this experiment the pressure drop across the sandpack is increased in a series of steps using a pressure regulator and the steady-state gas flow rate measured at each step. With pressure gradients so much lower in sandpacks than in consolidated core, one may doubt whether one has a strong foam or not. Resolving this question requires a plot like Figure 5, showing effective relative permeability to gas, and/or Figure 6, showing the effective relative permeability to water, to verify that foam is in place. Typical values of k_{rw} in the presence of strong foam would be of order 0.001. Thus strong foam is created in this experiment, though the pressure gradients are not large.

CONCLUSIONS

Detailed conclusions are listed in the sub-sections on each task in the section on Results and Discussion above. Important overall conclusions include the following:

1. Plots of pressure gradient as a function of superficial velocities of gas and liquid do not all fit the two regimes previously identified by Alvarez *et al*. (2001). In some cases, in place of the low-quality regime, where pressure gradient is expected to be independent of water superficial velocity, pressure gradient *decreases* with increasing water superficial velocity. There are a few examples of this behavior in the literature and our own laboratory data, but we are unsure of the explanation. The trend is consistent with the foam-viscosity model of Hirasaki and Lawson (1985), but only if both bubble size and the extent of gas trapping are constant, independent of injection rates.
2. Preliminary experimental results for foam with polymer suggest that foam generation with polymer present requires higher injection rates than without polymer. This suggests that foam is less stable with polymer than without.
3. Initial experimental results were obtained in a new set of experiments on foam generation with limited pressure gradient in sandpacks. Initial results are in line with previous experimental studies in our laboratory.

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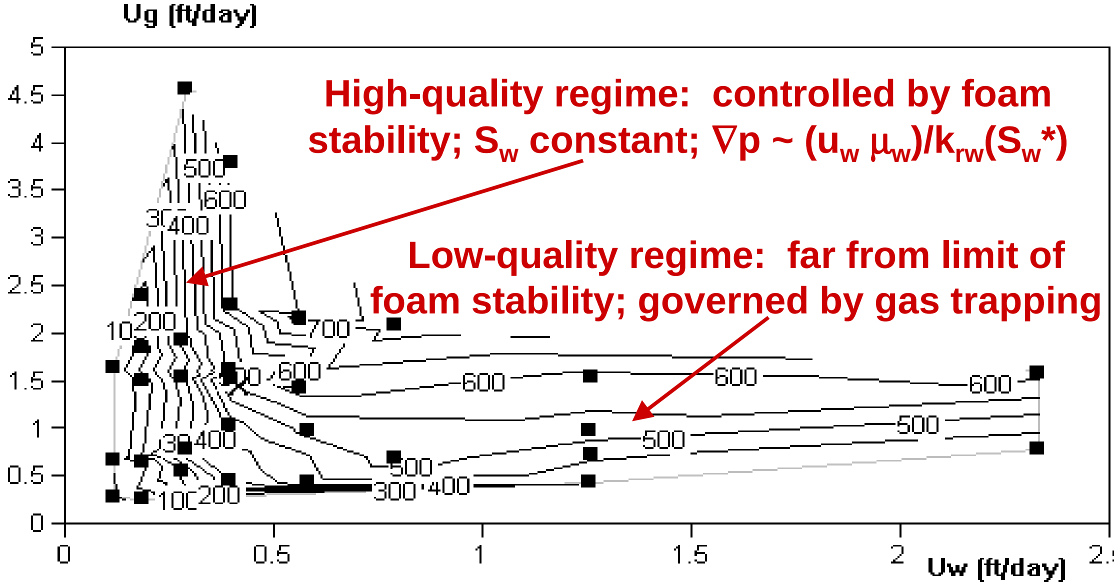

Figure 1. Steady-state pressure gradient as a function of superficial velocities of gas (U_g) and water (U_w) for one N_2 foam formulation in a Berea core, from Alvarez *et al*. (2001), illustrating the two steady-state strong- foam regimes.

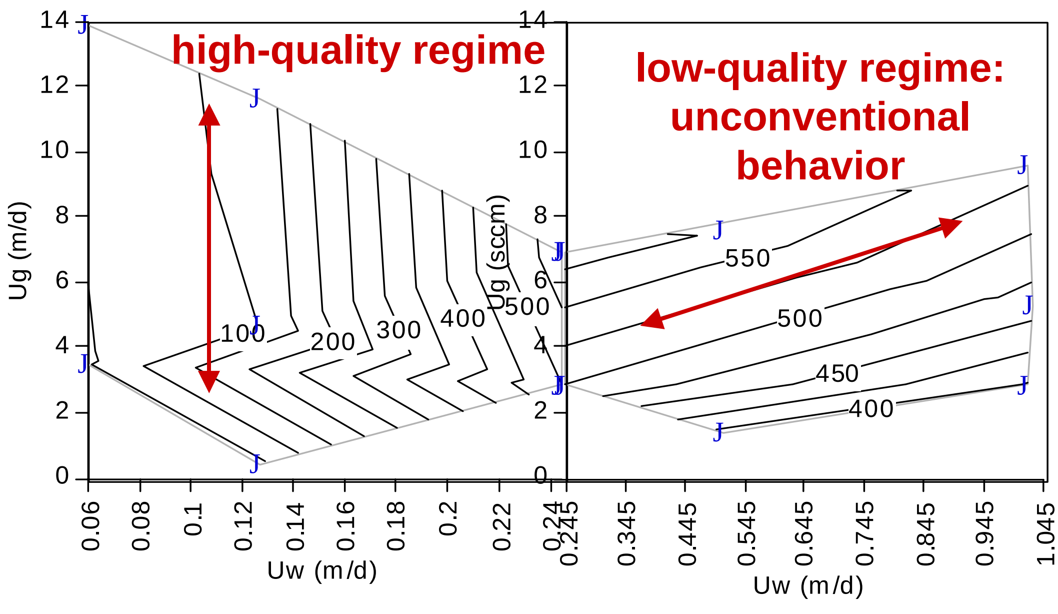

Figure 2. New data: steady-state pressure gradient as a function of superficial velocities of gas (U_g) and water (U_w) for one N_2 foam formulation in a sandpack; 1% AOS in 0.1 wt % Na^+, 0.05 wt % Ca^{++}. Similar plots for this surfactant formulation with polymer added will help identify the interactions of polymer with foam. Note change of scale at border between the two regimes.

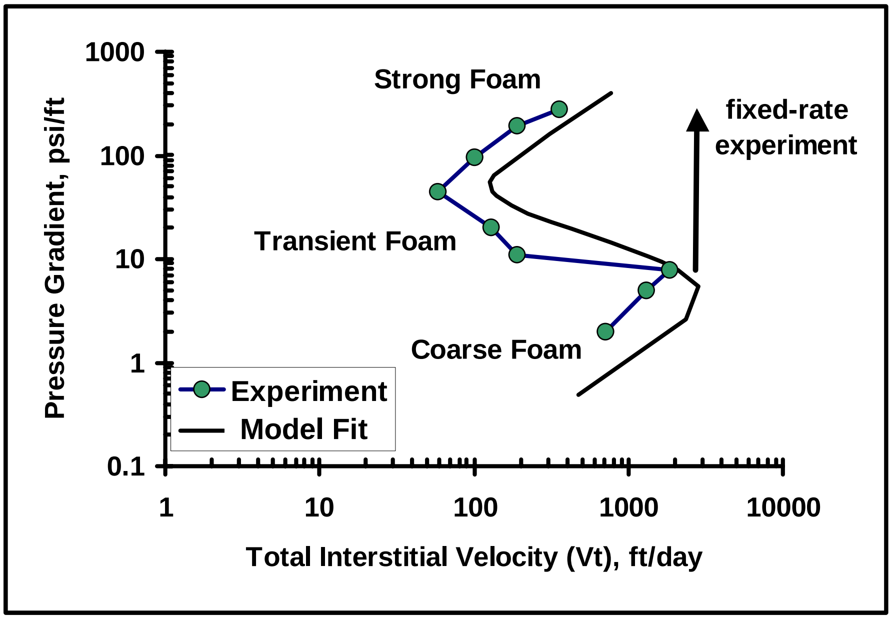

Figure 3. Laboratory data for foam generation in a Berea core (Gauglitz *et al*., 2002) fit by a population-balance model that incorporates foam generation triggered by pressure gradient (Kam and Rossen, 2002). In this example foam quality and pressure gradient are held fixed in both the experiment and the model, and total interstitial velocity responds to the creation of and rheology of foam.

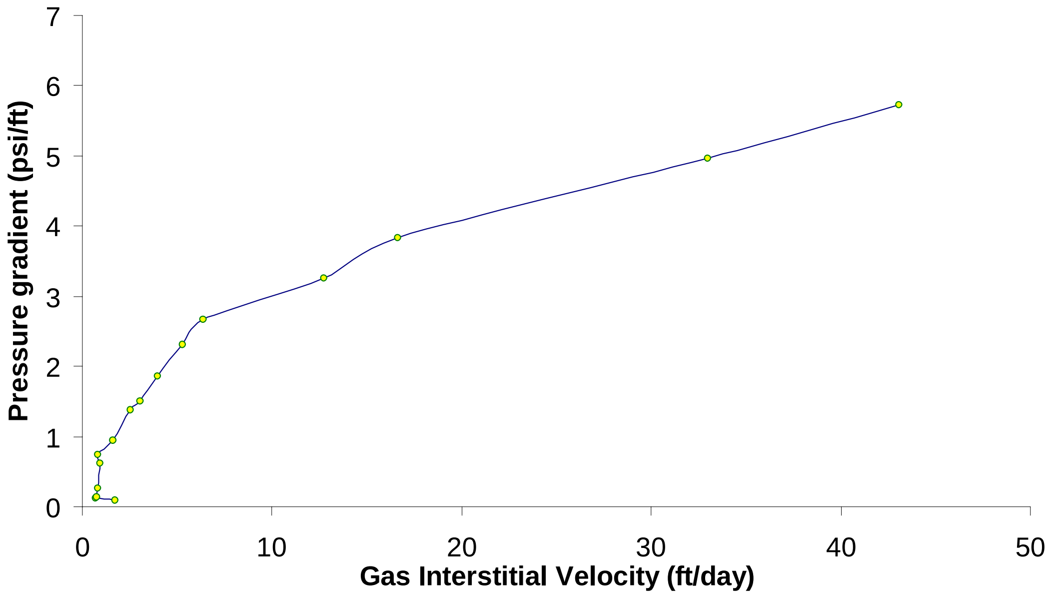

Figure 4. New laboratory data for foam generation in a sandpack (1% surfactant concentration, 5 darcy, liquid velocity 1.29 ft/day). In this example liquid superficial velocity and pressure gradient are held fixed, and gas flow rate responds to the creation and rheology of foam.

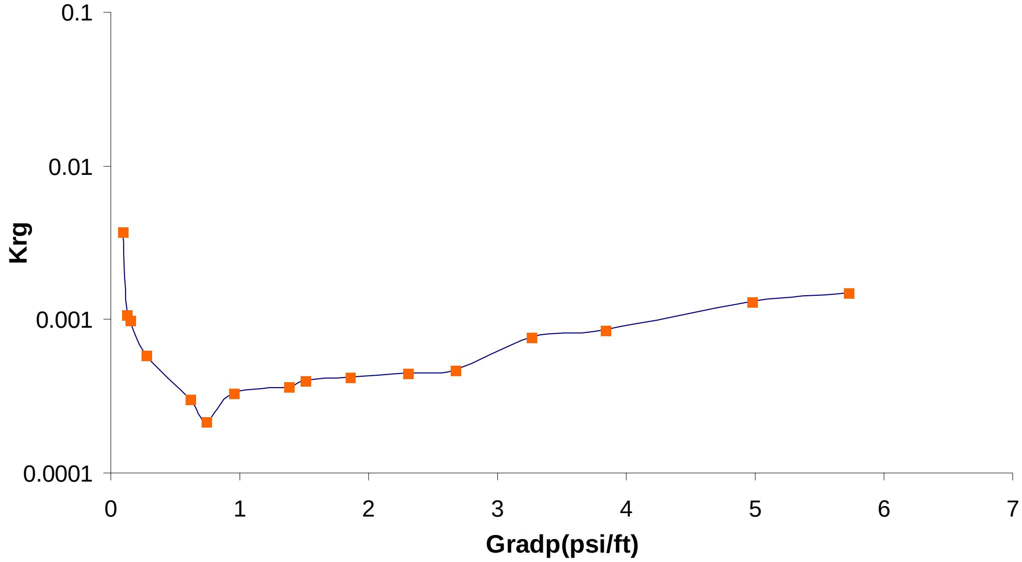

Figure 5. Apparent gas relative permeability from experiment in Figure 4, assuming for simplicity that all the effect of foam is incorporated into the gas relative permeability. Strong foams typically reduce apparent gas relative permeability to 0.001 or less, so these data indicate that a strong foam has been created. The apparently small pressure drop across the sandpack does not mean that strong foam is not created.

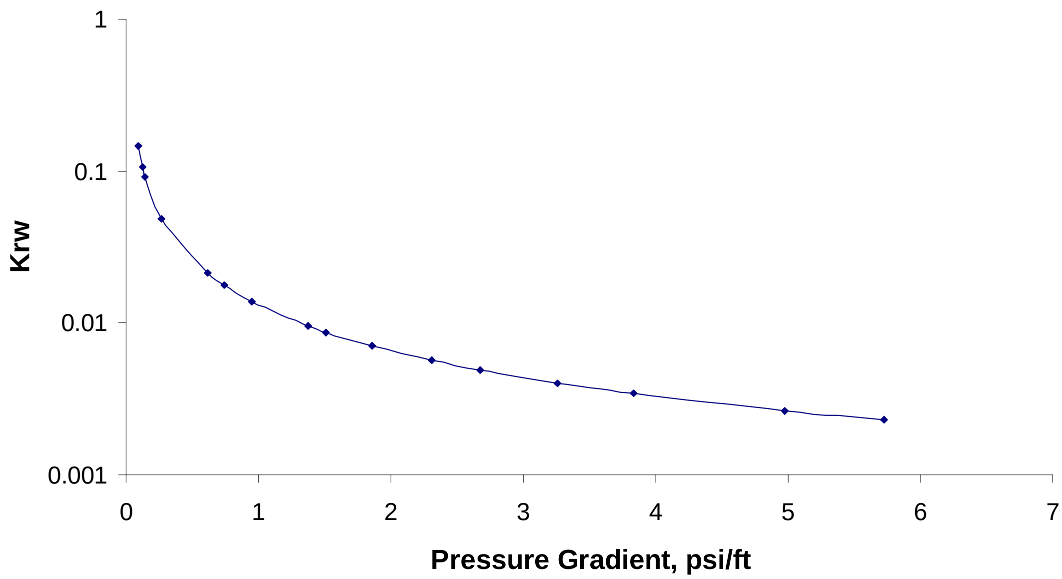

Figure 6. Water (aqueous-phase) relative permeability from experiment in Figure 4. Strong foams reduce apparent water relative permeability to values of the order of 0.001, so these data indicate that a strong foam has been created. The apparently small pressure drop across the sandpack does not mean that strong foam is not created.