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 2 and 3.

Research on Task 2 focused on experiments on gas trapping during liquid injection. A novel apparatus, similar to that in Kibodeaux and Rossen (1997), monitors average water saturation in a core moment-by-moment by weighing the core. Our experiments find that water saturation increases more during liquid injection than previously conjectured - in other words, less gas is trapped by liquid injection than previously thought. A number of unexpected trends in behavior were observed. It appears that these can be reconciled to previous theory of gas trapping by foam (Cheng *et al.*, 2001) given that the experimental conditions were different from previous experiments. Results will be described in detail in the PhD dissertation of Qiang Xu, expected to be completed in early 2003.

Regarding Task 3, recent laboratory research in a wide range of porous media shows that creating foam in steady flow in homogeneous media requires exceeding a minimum pressure gradient (Gauglitz *et al.*, 2002). Data fit trends predicted by a theory in which foam generation depends on attaining sufficient ∇p to mobilize liquid lenses present before foam generation. Data show three regimes: a coarse-foam regime at low ∇p, strong foam at high ∇p, and, in between, a transient regime alternating between weaker and stronger foam.

We for the first time incorporated into a population-balance foam model a bubble-creation function that depends on pressure gradient (Rossen and Gauglitz, 1990). The new model reproduces the three foam regimes seen in the laboratory, the abrupt

occurrence of foam generation at a threshold velocity or pressure gradient, hysteresis in experimental results, the interplay between foam stability and foam generation, the effect of injected liquid fractional flow on foam generation, and foam behavior in the high-quality and low-quality steady-state strong-foam regimes. The details of the lamella-creation function have little effect on rheology of strong foam, which is controlled by other mechanisms. The predicted fractional-flow curves are complex. This model is a necessary step toward quantitative prediction of foam performance in the field.

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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

We began constructing our apparatus, selecting surfactants and polymers for use in experiments, and quantifying polymer rheology in the absence of foam. No other significant results were obtained in this period.

TASK 2: GAS TRAPPING

Research on Task 2 focused on new experiments on gas trapping during liquid injection. A novel apparatus, similar to that in Kibodeaux and Rossen (1997), monitors average water saturation in a core moment-by-moment by weighing the core. Our experiments find that water saturation increases more during liquid injection than previously conjectured - in other words, less gas is trapped by liquid injection than previously thought (*cf*. Zeilinger *et al*., 1995). The trapped-gas saturation during liquid injection decreased with increasing quality (gas fraction) of the previously injected foam. In these experiments relatively high-quality (high gas-fraction) foams were used, so the increase in liquid velocity after foam injection is greater. As a result, pressure gradient increased in these experiments during liquid injection (Figure 1); all our previous experiments (Kibodeaux *et al*., 1994; Zeilinger *et al*., 1995; Rossen and Wang, 1999) had seen a decrease in pressure gradient during liquid injection.

This finding may be significant for attempt to divert liquid injection with foam. The early modeling work of Kibodeaux *et al*. (1994) concluded that the decline in pressure gradient seen shortly after liquid injection begins reduces the ability of foam to overcome the effects of permeability and divert the flow of liquid.

Other surprising trends in behavior were observed. As liquid injection follows foam, there is a rapid rise in liquid saturation in the core, as expected (Figure 1). For a period after this, there is a gentle rise in liquid saturation, while pressure gradient rises in some sections of the core. Later on, as pressure gradient in the downstream sections falls over time, average liquid saturation also falls in the core - in spite of the fact that no gas is being injected. Finally, liquid saturation rises slowly again.

These apparent contradictions can be reconciled using previously developed theory of gas trapping and gas dissolution. An increase in pressure gradient would have been predicted by the model of Cheng *et al*. (2002) for a case where initial foam quality was high and liquid was later injected at the same volumetric rate as foam. The possibility was not explicitly foreseen because all previous experiments had involved relatively low-quality foams.

The apparently contradictory behavior of average water saturation and pressure gradient can be understood by considering the effects of gas dissolution and expansion of trapped gas. In previous work, pressure gradient decreased during liquid injection and gas expanded during this period. Thus gas saturation everywhere was at its maximum trapped-gas saturation for the given pressure gradient (Cheng *et al*., 2002). In these experiments, pressure gradient increased during liquid injection, and gas was compressed. As a result, gas saturation was below its residual saturation, especially in upstream sections of the core. Then, as unsaturated liquid entered the core and dissolved a fraction of this trapped gas, it raised liquid mobility locally. As the dissolution wave moved toward the outlet of the core, pressure in the upstream sections decreased, and gas there expanded, reducing liquid saturation. Most of the pressure drop was in the downstream sections, where gas saturation was being reduced by dissolution. Therefore average gas saturation rises even as overall pressure drop across the core falls.

Some aspects of these experiments are still under examination. Results will be published in the PhD dissertation of Qiang Xu, expected to be finished in early 2003 (Xu, 2003).

TASK 3: FOAM GENERATION

We incorporated the insights of our previous experimental work into a population-balance foam model and analyzed the behavior of this model at steady state. The paper describing the experimental work has appeared in *Chemical Engineering Science* (Gauglitz *et al*., 2002). During this period we incorporated a foam-generation algorithm where the rate of foam creation increases with increasing pressure gradient into a population-balance model for foam (cf. Falls et al., 1988). The results of this work are as follows:

The model is not predictive or complete. Some of its simplifications and shortcomings are described by Kam and Rossen (2002). In addition, it shares with all population-balance models the inherent ambiguity arising from the inability to distinguish effective gas relative permeability and gas viscosity, or separately measure lamella creation and lamella destruction rates, in porous media. Nonetheless, one can draw the following conclusions:

1. A population-balance model incorporating a lamella-creation function that depends on ∇p (Rossen and Gauglitz, 1990) fits the following features observed in foam-generation experiments (Gauglitz *et al*., 2002):
   a. There are three flow regimes (Figure 2): a coarse-foam regime at low ∇p, in which flow rate increases with increasing ∇p; a transient regime at intermediate ∇p, in which flow rate decreases with increasing ∇p; and a strong-foam regime at high ∇p, in which flow rate again increases with increasing ∇p.

b. A qualitative fit to laboratory data is obtained for the three foam regimes in consolidated core and a beadpack (*cf*. Figure 2), in experiments with fixed ∇p and either fixed foam quality or fixed liquid injection rate.
c. The predicted minimum gas velocity for foam generation decreases as water fractional flow increases, in agreement with experiments. (The model disagrees with theory in that it predicts that the minimum pressure gradient for foam generation increases as liquid fractional flow increases.)
d. Both the minimum gas velocity and minimum pressure gradient for foam generation decrease as the formulation is altered to make the foam more stable, i.e. to give higher ∇p in the strong-foam regime.
e. The strong-foam regime (Figure 3) comprises a high-quality regime, in which ∇p is independent of gas flow rate, and a low-quality regime, in which ∇p is nearly independent of liquid flow rate (Alvarez *et al*., 2001). The latter is observed if one imposes a lower limit on bubble size.

2. The details of the lamella-creation function have little effect on the high-quality and low-quality strong-foam regimes, which are controlled by other mechanisms. Therefore, a good model fit to steady-state strong-foam behavior is not itself proof of validity for the lamella-creation algorithm used in a population-balance model.
3. If pressure gradient is plotted as a function of flow rates of gas and liquid, the model predicts a folding-over of this surface in an catastrophe (Poston and Stewart, 1978), where the transient regime originates. With current model parameters, this feature would appear at extremely dry, high flow rates and would be hard to observe in the laboratory.
4. The fractional-flow curves predicted by the model are complex, including both multiple-valued functions and isolated loops (Figure 4). Predicting displacements from these curves (*cf*. Zhou and Rossen, 1995; Rossen *et al*., 1999; Shan and Rossen, 2002) will require refinements in conventional fractional-flow theory.

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. New experimental results were obtained on gas trapping during liquid injection after foam. Results were unexpectedly complex, but, for the most part, they can be reconciled with earlier ideas about gas trapping. The extent of gas trapping decreased with increasing foam quality.
2. A new population-balance model for foam incorporating foam generation by mobilization rather than snap-off is not predictive, but nevertheless offers important insights into foam generation and steady-state foam properties. The model fits the complex behavior and multiple steady states observed in the laboratory as a function of applied pressure gradient. It also fits trends in foam generation with foam quality and stability of the steady-state foam. Once strong foam is created, however, its properties are not strongly dependent on the mechanisms by which foam is created; rather, steady-state properties are controlled by other mechanisms. One cannot infer foam-generation mechanisms from the behavior of strong foam at steady state.

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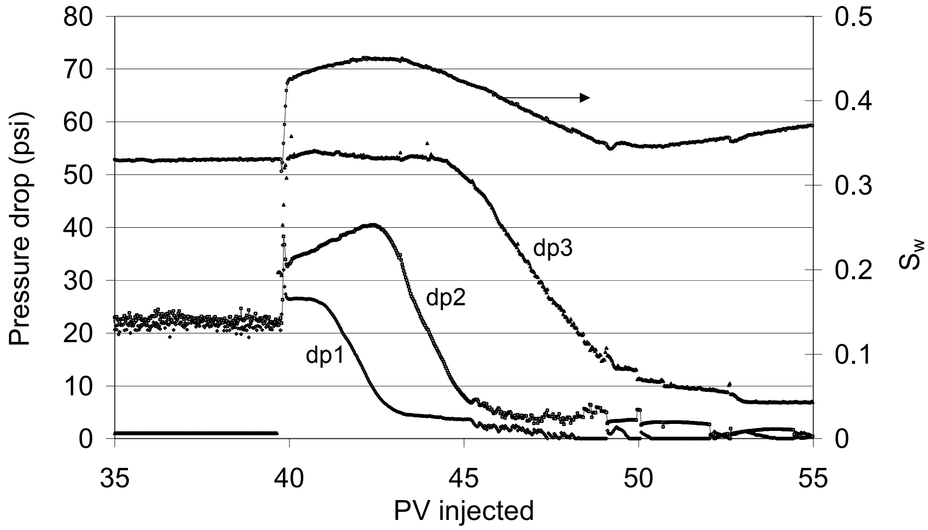

Figure 1. Data from coreflood experiment on gas trapping with foam. Shortly before 40 PV injection, gas injection ceases and liquid injection rate increases to approximate total volumetric injection rate of foam. Water saturation rises by about 10%, while pressure drops (dp) in all three sections of the core increase. The subsequent rise in pressure drop in section 2 (dp2) is not fully understood. The subsequent rise, fall, and rise in water saturation (top curve) during injection of liquid can be understood as the separate effects of gas dissolution and of expansion of gas still trapped as pressure falls off in the core. Details are in Xu (2003).

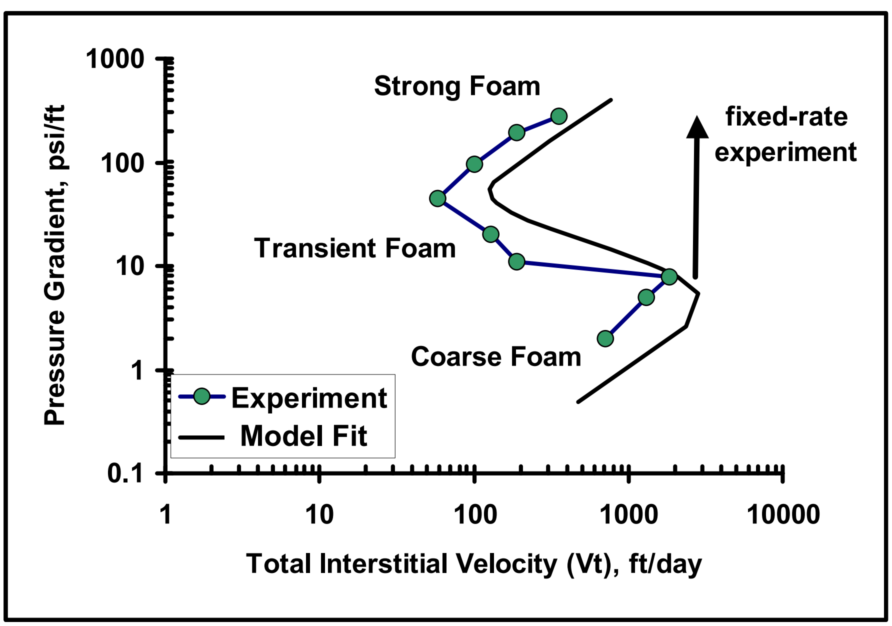

Figure 2. Laboratory data for foam generation in a Berea core (Gauglitz *et al*., 2002) fit by a population-balance model that incorporates foam generation triggered by pressure gradient. In this example foam quality and pressure gradient are held fixed in both the experiment and the model, and total flow rate responds to the creation and rheology of foam.

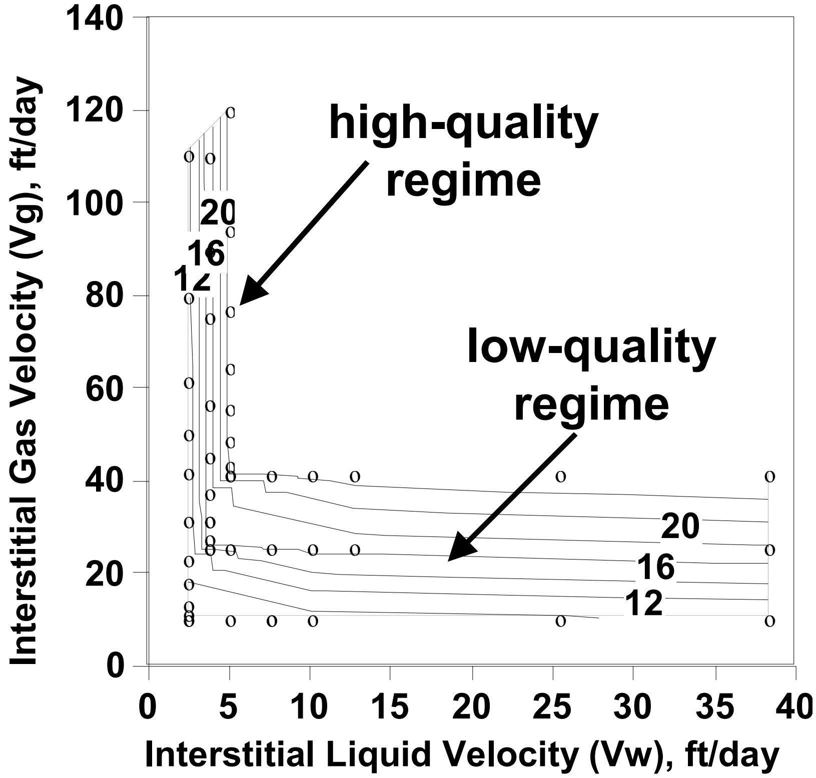

Figure 3. Steady-state pressure gradient as a function of interstitial velocities of gas and liquid in a beadpack predicted by a population-balance foam model that incorporates foam generation triggered by pressure gradient. Note high-quality regime (vertical ∇p contours at upper left) and low-quality regime (lower right). Circles represent points where model properties were calculated, not data points.

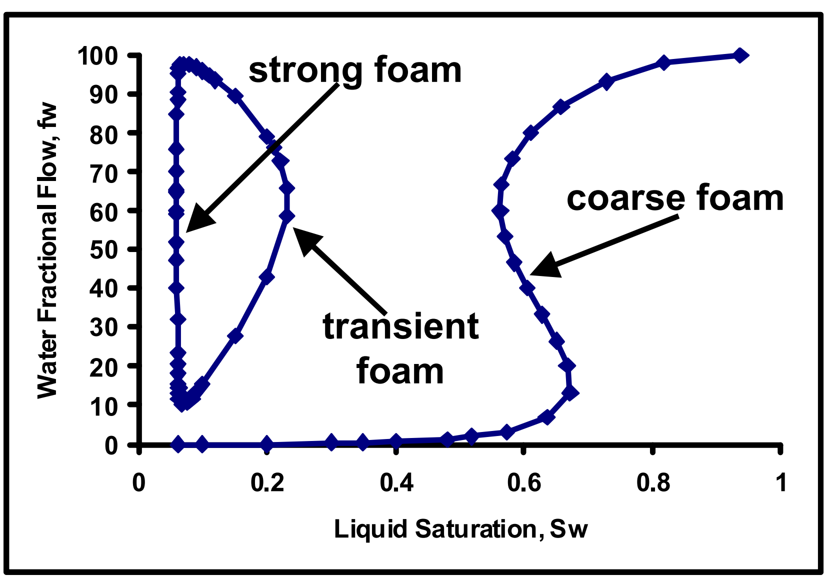

Figure 4. Example fractional-flow curve predicted by population-balance foam model that incorporates foam generation triggered by pressure gradient.