DEVELOPMENT OF MORE-EFFICIENT GAS FLOODING APPLICABLE TO SHALLOW RESERVOIRS

Semi-Annual Report for the Period
January 1, 2002 – June 30, 2002

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Date Report Issued: January 28, 2003

Work Performed under DOE Award Number DE-AC26-99BC15208

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Contract No. DE-AC26-99BC15208

The University of Texas at Austin
1 University Station, C0300
Austin, TX 78712-1061

Contract Date: July 9, 1999

Anticipated Completion: Dec. 31, 2002 (no-cost extension)

ABSTRACT:

The objective of this research is to widen the applicability of gas flooding to shallow oil reservoirs by reducing the pressure required for miscibility using gas enrichment and increasing sweep efficiency with foam. Task 1 examines the potential for improved oil recovery with enriched gases. Subtask 1.1 examines the effect of dispersion processes on oil recovery and the extent of enrichment needed in the presence of dispersion. Subtask 1.2 develops a fast, efficient method to predict the extent of enrichment needed for crude oils at a given pressure. Task 2 develops improved foam processes to increase sweep efficiency in gas flooding. Subtask 2.1 comprises mechanistic experimental studies of foams with N₂ gas. Subtask 2.2 conducts experiments with CO₂ foam. Subtask 2.3 develops and applies a simulator for foam processes in field application.

Regarding Task 1, several very important results were achieved this period for subtask 1.2. In particular, we successfully developed a robust Windows-based code to calculate MMP and MME for fluid characterizations that consist of any number of pseudocomponents. We also were successful in developing a new technique to quantify the displacement mechanism of a gas flood – that is, to determine the fraction of a displacement that is vaporizing or condensing. These new technologies will be very important to develop new correlations and to determine important parameters for the design of gas injection floods.

Regarding Task 2, several results were achieved: 1) A detailed study of the accuracy of foam simulation validates the model with fits to analytical fractional-flow solutions. It shows that there is no way to represent surfactant-concentration effects on foam without some numerical artifacts. 2) New results on capillary crossflow with foam show that this is much less detrimental than earlier studies had argued. 3) It was shown that the extremely useful model of Stone for gravity segregation with foam is rigorously true as long as the standard assumptions of fractional-flow theory apply. Without this proof, it was always possible that this powerful model would break down in some important application.

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OBJECTIVES

The objective of this research is to widen the applicability of gas flooding to shallow oil reservoirs by reducing the pressure required for miscibility using gas enrichment and increasing sweep efficiency with foam. Task 1 examines the potential for improved oil recovery with enriched gases. Subtask 1.1 examines the effect of dispersion processes on oil recovery and the extent of enrichment needed in the presence of dispersion. Subtask 1.2 develops a fast, efficient method to predict the extent of enrichment needed for crude oils at a given pressure. Task 2 develops improved foam processes to increase sweep efficiency in gas flooding. Subtask 2.1 comprises mechanistic experimental studies of foams with N₂ gas. Subtask 2.2 conducts experiments with CO₂ foam. Subtask 2.3 develops and applies a simulator for foam processes in field application.

RESULTS AND DISCUSSION

TASK 1: REDUCE MMP WITH GAS ENRICHMENT

SUBTASK 1.2: ROBUST CALCULATION OF MMP AND MME

Local displacement efficiency from gas injection is highly dependent on the minimum miscibility pressure (MMP) or minimum miscibility enrichment (MME). Analytical methods, which are inexpensive and quick to use, have been developed to estimate MMP's for complex fluid characterizations. Published methods (Johns and Orr, 1986; Jessen *et al.*, 1998; Wang and Orr, 2002), however, often require estimation of numerous parameters and little has been written with regard to method robustness. This report outlines a simplified and robust method for MMP or MME calculation.

The approach relies on finding key crossover tie lines for a dispersion-free displacement using method of characteristic theory (MOC). The new method, however, differs from published methods by significantly reducing the number of equations and unknown parameters, and by providing a fast and robust method that can avoid trivial and false solutions. We demonstrate the improvements by calculation of the MMP and MME for a variety of gas/oil systems and also give new analytical solutions for constant K-value systems that give insight into the nature of the false solutions. We consider several widely varying fluid characterizations to demonstrate the robustness of the method. All examples use the Peng-Robinson equation-of-state (PREOS).

Figure 1.1 shows the key tie-line lengths for a simple four-component system. The three-component oil (C₁, C₆, C₁₆) displacement by two-component gas is a CV drive. Figure 1.1 verifies the CV displacement in that the crossover tie line becomes a critical tie line first at the MME of about 59.6% C₁ and 40.4% C₃. The oil tie-line length remains constant with enrichment because pressure does not change. The gas tie line has zero length at about 46.6% C₁ and 53.4% C₃. Thus, if the displacement had been considered a condensing drive, the error in the estimated MME would be large (13% C₃ enrichment).

Figures 1.2 and 1.3 show the calculated tie-line lengths for the seven-component systems considered by Uleberg and Hoier (2002). For lean gas injection they report a MMP of 6909 ± 147 psia as measured by slim-tube experiments. For enriched-gas injection, they estimate the MMP to be 4777.5 ± 73.5 psia. Thus, as expected the MMP is significantly lower when the gas is enriched with solvent. The calculated MMP by the

simplified method is in perfect agreement with these values: 7007 psia for lean gas injection and 4838 psia for enriched-gas injection. For lean gas injection, the first crossover tie line controls the development of miscibility and the displacement is a CV drive. The displacement is also a CV drive for the enriched-gas case, but the third crossover tie line controls the development of miscibility. Thus, we expect the enriched-gas drive to be more condensing than the lean-gas drive.

Last, we consider a displacement of twelve-component oil by five-component gas, as previously reported by Solano *et al.* (2002). In this enriched-gas flood, the lean gas from the separator is enriched with a five-component solvent. Figure 1.4 shows all key tie-line lengths as the lean gas is enriched with solvent. After 4% enrichment with solvent, the fourth crossover tie line becomes the shortest key tie line. The fourth crossover tie line eventually has zero length at the MME of 57.2%, which agrees well with the approximate reported value of 60% (confidential verbal communication with an oil company sponsor). Thus, the displacement mechanism is CV.

The simplified method for analytical calculation of MMP is much faster than experimental or simulation methods. For the twelve-component system of Fig. 1.4, the calculation from the pure gas solution to the lean gas solution to the MME (at increments of 1% enrichment) took less than five minutes on a Pentium II personal computer or about 2 seconds per increment. Thus, the analytical method has significant potential for improving the characterization of fluids or in providing new correlations.

Besides speed, the main advantage of the analytical approach is that the estimated MME and MMP are independent of dispersion. As shown by Solano *et al.* (2001) dispersion can significantly affect the estimation of MMP or MME for some fluid characterizations. In such cases, estimates of MME or MMP from slim tube experiments are likely too large because recovery trends are affected by physical dispersion.

The main disadvantage with the analytical approach is that a good fluid characterization by an EOS is required (this is also true for simulation methods). Although this is a disadvantage compared to slim tubes, the analytical method could be used to determine what additional PVT data should be obtained to improve fluid characterizations. The new Windows-based code can be used to determine the reduction in the MMP as a function of gas enrichment. Recently, Shell International Inc. is using the code for the determination of MMP.

TASK 2: INCREASE SWEEP EFFICIENCY WITH FOAM

During this period we continued our studies of N₂ foam, examining liquid injectivity in SAG foam processes and stability of foam during gas injection in a SAG process, and behavior of CO₂ foam in a sandpack. We expect to report on these studies in the next semi-annual report.

Accuracy of Foam Simulation. An detailed study of accuracy of and numerical artifacts in foam simulation with the "fixed-P_c*" foam model developed at UT was completed by Liang Cheng and included in his dissertation (Cheng, 2002). This model can describe foam flow in both low- and high-quality regimes, as well as shear-thinning behavior in low-quality regime. The effects of foam model parameters on foam behavior are examined, and a procedure for fitting the foam model parameters to foam data is described in the dissertation. Comparison between simulation and fractional-flow methods for the same foam-injection and post-foam liquid-injection processes validated the foam simulator, and revealed two numerical artifacts: fluctuations of water saturation ahead of foam front, and a small delay in foam propagation.

Two models of the dependence of foam strength on surfactant concentration were studied. Making foam generation a nonlinear function of surfactant concentration can artificially accelerate foam propagation; making foam suddenly appear at a threshold concentration can artificially slow foam propagation. Both artifacts depend on numerical or physical dispersion. Both artifacts might be more severe in simulations using fewer grid blocks or less rigorous control of numerical dispersion than in UTCHEM (Liu, 1993). Simulation practitioners should check the extent of numerical dispersion of surfactant concentration and its effect on foam propagation. The results confirm Zeilinger's (1996) finding that, in the absence of dispersion, the foam front propagates as an indifferent wave, i.e., a shock front, with velocity independent of how foam strength depends on surfactant concentration.

Capillary Crossflow with Foam. Earlier Zhou and Rossen (1995) argued that the success of foam in diverting flow between geological layers differing in permeability depended on the extent of capillary contact between the layers. If the layers were separated by an impermeable barrier, foam was expected to be successful. In the limit of capillary equilibrium, however, higher capillary pressure in the lower-permeability layer would draw the water out of the higher-permeability layer and break foam there. The result would be anti-diversion: foam blocking the low-permeability layer but not the high-permeability layer. Later Rossen and Lu (1996) and Rossen *et al.* (1999) sought to define the conditions that approach this state of capillary equilibrium. Cheng's dissertation (2002) follows up this study.

Cheng concludes that in flow of foam through adjacent layers, capillary-cross flow does weaken foam in the high-permeability layer, but it does not significantly hurt sweep efficiency between adjacent layers, contrary to the conclusions of Rossen and Lu (1997) and Rossen *et al.* (1999). Viscous crossflow gives an even frontal advance of foam in all case we examined in this study, except one case with extremely slow injection rate and long, narrow layers. Even in that case, the gas bank still sweeps both layers ahead of the foam.

The overall mobility can be reduced or increased by capillary crossflow, depending on the magnitude of capillary crossflow reflected in the product of two dimensionless groups. This effect can have a small positive or negative effect on diversion from a pair of adjacent layers, differing somewhat in permeability, to another distant layer.

A limited contrast in ranges of permeability, model parameters, injection rates, and rectilinear layer geometries were tested for crossflow in this study. More factors may need to be tested: foam quality, partially effective shale barriers between layers, permeability anisotropies, gravity effects, different foam models, and radial flow geometry. An important limiting case of capillary crossflow would be foam flow through a natural fracture. This case deserves further study before final conclusions are drawn.

Simulations with different extents of grid refinement suggest that the gridding effect on simulation results is insignificant; if anything, relatively coarse grids (layers 5 grid blocks wide) tend to overstate, not understate, the effect of capillary crossflow.

Gravity Override with Foam. The model of Stone (1982) and Jenkins (1984) for gravity segregation in steady, horizontal gas-liquid flow in homogeneous porous media is extremely useful and apparently general, but without a sound theoretical foundation. The model fits simulations of gas-water flow over a wide range of parameter values. Still more remarkably, the model fits gravity segregation in simulation of foam injection as well (Shi and Rossen, 1998b), in spite of the complexity of foam behavior, the extremely

large reductions in gas mobility caused by foam, and the abrupt collapse of foam often observed over a narrow range of water saturation. In earlier research, Shi and Rossen (1998a) and Cheng *et al.* (2000) varied injected foam quality, foam strength, foam mechanistic model, flow rates, reservoir dimensions and properties, and even finite-difference grid refinement over a wide range of values with virtually no deviation from predictions of Stone and Jenkins.

The implications of Stone and Jenkins' model are profound: For a given reservoir and density difference between phases, the only way to increase the distance gas and water travel together before complete gravity segregation is to increase the lateral pressure gradient in the reservoir, at the cost, of course, of increased injection-well pressure. Equivalent improvements are predicted, for instance, from injecting a strong foam at low flow rates, a weak foam at higher rates, or no foam at all at very high rates. Moreover, if injection-well pressure is limited, it may be impossible to achieve a desired improvement in vertical sweep. (These conclusions, apply only to continuous-injection foam processes. Shi and Rossen (1998a) and Shan and Rossen (2002) show that alternating-slug foam processes with sufficiently large slugs (larger than those envisioned by Stone and Jenkins) can achieve much better vertical sweep without adversely affecting injection-well pressure.)

Thus Stone and Jenkins' model fits a wide range of simulation results and some laboratory data for gas-water flow with or without foam. However, the theoretical justification for the model was uncertain. That meant that it was always possible that the model would fail to apply in some crucial case.

Working with Dr. C. J. van Duijn of the Department of Mathematics and Computer Science of Eindhoven University of Technology in The Netherlands, we developed a proof that this model applies to steady-state gas-liquid flow, and also foam flow, as long as the standard assumptions of fractional-flow theory apply. We solved rigorously for the lateral position of the point of complete segregation of gas and water flow, which agrees with that in Stone's original paper.

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Figure 1.1-Example displacement of three-component oil by two-component gas (a four-component system). The MME occurs when the crossover tie line is zero length at 59.6% C_1 and 40.4% C_3 . Thus, the system is a combined condensing/vaporizing (CV) drive.

Figure 1.2-Lengths of key tie lines for displacement of seven-component oil by a five-component lean gas (seven-component system reported by Uleberg and Hoier (2002)). The slim tube measured MMP is 6909 ± 147 psia. The calculated MMP by the simplified method is 7007 psia. Crossover tie line 1 controls miscibility and the displacement is CV.

Figure 1.3-Lengths of key tie lines for displacement of seven-component oil by a five-component lean gas (seven-component system reported by Uleberg and Hoier (2002)). The slim tube measured MMP is 4777.5 ± 73.5 psia. The calculated MMP by the simplified method is 4838 psia. Crossover tie line 3 controls miscibility and the displacement is CV.

Figure 1.4-Lengths of key tie lines for displacement of twelve-component oil by five-component enriched-gas. The calculated MME occurs when the lean gas is enriched to 57.2% of the solvent. Crossover tie line 4 controls miscibility and the displacement is CV.