INTERFACIAL EFFECTS IN THE RECOVERY
OF RESIDUAL OIL BY DISPLACEMENT:
STUDIES AT NORTHWESTERN UNIVERSITY

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Objective A: Further Analysis of the Displacement of Oil by Water in Porous
Media

abstract

We began our investigation with a static analysis of the displacement of an oil segment by an aqueous surfactant solution through a capillary whose radius is a sinusoidal function of axial position (Oh and Slattery 1976). While this discussion is helpful in clarifying some aspects of the displacement problem, it can say nothing about the effects attributable to the surface viscosities. For this, we must recognize the displacement to be a dynamic process.

We have attempted to make our first dynamic problem as simple as possible while still preserving some degree of realism. We are currently analyzing the displacement of a gas by a liquid in a straight capillary tube of uniform diameter assuming that the interface moves with a constant speed. We are optimistic of having our first results within four months.

introduction

We have previously argued that both the surface shear and the surface dilatational viscosities may play significant roles in the recovery of residual oil by displacement with an aqueous surfactant solution (Slattery 1974). Conventional petroleum production from a field usually concludes with a partial displacement of the oil remaining in the reservoir either by water or by brine. For carefully selected, well-designed, good-performing operations, 50-70% of the oil originally in place is left behind at the end of conventional petroleum production (Geffen 1973). There is a critical value for the brine-crude oil surface tension above which this residual oil cannot be recovered by further water flooding under a given pressure gradient. When the surface tension is reduced below this critical value, the efficiency of residual oil recovery by displacement with an aqueous surfactant solution will increase as the sum of the water-oil surface viscosities is decreased. The effect of the reduction in the surface viscosities upon the efficiency of residual oil recovery is estimated to be comparable to the effect of a reduction in the surface tension.

A major objective of our research program is to check these conclusions.

Kanda and Schechter (1976) have studied experimentally the displacement of foams in porous media. They found that

1. the breakthrough time (which is inversely proportional to the rate of displacement of the foam) is increased by raising the surface tension and the surface shear viscosity, and
2. the displacement efficiency (closely related to the sweep efficiency) is increased by raising the surface shear viscosity.

We have just completed (and are currently preparing for publication) an analysis of foam displacement that comes to similar conclusions. This analysis has the same form as that given by Slattery (1974). Since the con-

clusions of this analysis relevant to the effects of the surface viscosities are backed by experimental data, we may be justified in attaching more significance to the effects of the surface viscosities in surfactant water flooding predicted by Slattey (1974).

Objective A of this research program is to model the displacement of a residual oil segment in a single pore by a surfactant solution. We hope in this way to obtain a quantitative estimate of the relative effects of the surface viscosities, of surface tension, of the wettability condition, and of the contact angle hysteresis. If, as we have predicted, the surface viscosities are shown to be significant parameters, we hope to use the results of these modeling studies in correlating experimental displacement data.

In what follows, we describe the preparations we have made during this past year for our first attempt to model displacement as a dynamic process.

displacement in a single pore

We began with a static analysis of the displacement of an oil segment by an aqueous surfactant solution through a capillary whose radius is a sinusoidal function of axial position (Oh and Slattey 1976). While this discussion is helpful in clarifying some aspects of the displacement problem, it can say nothing about the effects attributable to the surface viscosities. For this, we must recognize the displacement to be a dynamic process.

We have attempted to make our first dynamic problem as simple as possible while still preserving some degree of realism.

A pore is an irregular channel whose radius varies with axial position. Displacement of an oil segment through such an irregular channel is an unsteady-state process. For this reason, we have chosen to confine our attention in our first analysis to displacement in a straight capillary tube whose radius

is independent of axial position. Displacement under these conditions can be transformed into a steady-state problem by viewing the flow in a frame of reference in which the oil segment is stationary and the tube wall moves with an unknown speed parallel to its own axis.

A major difficulty in this analysis is associated with the moving common line or moving three phase line of contact formed by the intersection of the oil-water phase interface with the pore wall. For this reason, we have chosen to confine our attention initially to the displacement of a single oil-water phase interface. A later study will extend this analysis to the displacement of an oil segment (bounded by two oil-water interfaces).

Figure 1 illustrates the rolling motions to be expected in the neighborhood of the interface (Dussan V. and Davis 1974; Allen and Benson 1975). The flow patterns are sketched assuming that the oil-water interface is stationary and the tube wall moves with a speed U in the negative z direction. In order to eliminate some of the complexity, we have confined our attention initially to the displacement of a gas by a liquid (when the viscosity ratio $\mu_2/\mu_1 \rightarrow 0$).

Huh and Mason (1975) have studied a similar problem but with two differences.

- i) They assumed that the contact angle is close to 90° .
- ii) They neglected the effects of the surface viscosities and the surface tension.

We will compare our results for the above limiting case with those of Huh and Mason (1975).

summary of first problem to be solved

We are currently analyzing the displacement of a gas by a liquid as shown in Figure 2. The assumptions made can be summarized as follows.

1. The tube is a straight cylinder.
2. Entrance and exit effects are neglected. This is equivalent in saying that the cylinder extends to infinity in both direction.
3. The frame of reference in which the problem is solved is chosen such that the liquid-gas interface is stationary and the cylinder wall moves with a speed U in the negative z direction.
4. Inertial effects are neglected.
5. Effects of gravity are neglected.

We are not neglecting mass transfer of surfactant to and from the phase interface. Instead we are carrying out a perturbation solution in which the perturbation parameter is proportional to the displacement speed U . At the first perturbation, the velocity and pressure distributions correspond to those expected with the equilibrium surfactant distribution and with a spherical phase interface. We believe that this first-order perturbation solution is relevant to treating the creeping motion of an oil segment expected between Haines jumps in an irregular pore.

The objective of the computation will be to determine the dependence of the pressure difference (beyond that predicted by Poiseuille flow) upon the surface viscosities.

numerical technique currently favored

We must solve the equation of continuity and the equation of motion for the bulk phase consistent with the jump mass balance and the jump momentum balance for the gas-liquid phase interface. We propose to construct an iterative solution in which we begin by assuming the velocity distribution at the gas-liquid interface. With this boundary condition, we can solve the equation of continuity and the equation of motion to determine the pressure and velocity distributions within the bulk phase. We can now use these results

to calculate the stress distribution exerted by the bulk phase on the interface. This allows us to determine a second approximation for the surface velocity distribution by solving the tangential component of the jump momentum balance at the interface. This calculated surface velocity distribution can now be used as the starting point for the next iteration.

There are several techniques available for solving a fluid mechanics problem such as that outlined above.

We could use a finite-element method in one of several variations (Atkinson et al. 1969; Smith and Brebbia 1973; Lee 1974). We could construct a finite-difference solution in one of several forms (Vrentas and Duda 1973; Wagner 1975).

We currently favor an integral equation solution similar to that used by Papamichael and Symm (1975). The advantage of this integral equation method is that we can determine the pressure, velocity, and the normal derivatives of velocity in the limit as the gas-liquid interface is approached without solving for the pressure and velocity distribution within the bulk phase.

We are currently programming this calculation and are optimistic of having our initial results within the next four months.

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Figure 1. Rolling Nature of Two Phase Flow in a Straight Cylinder.

Figure 2. A Stationary Interface in a Straight Cylinder Pore Moving with Constant Speed U .

Objective B: The Measurement of Small Interfacial Tension by the Rod-in-Free
Surface Meniscal Breakoff Method

During this quarter (December 1, 1976 to February 28, 1977) a pressure-sensitive breakoff detection system was designed, constructed and tested. Meniscal breakoff heights have previously been detected by interruption of an electrical signal. With simple systems (i.e., no surfactants present) this procedure works well, giving clean, reproducible breakoff indications; with low tension systems containing surfactants the early time behavior is acceptable, giving apparent interfacial tensions comparable to those derived from spinning drop data. However, after the interface has aged for 6 to 12 hours the breakoff detection becomes uncertain and erratic. This may be due to formation of a third phase at the interface; such a development could interfere with the expected interruption of electric current upon meniscal breakoff. In-other-words, breakoff indicated by erratic behavior of the electric sensor may signify that the interface can no longer be "classically" analyzed. Inferring values of interfacial tension with a theory of the instrument dependent upon the Young-Laplace equation can be misleading if the interface no longer behaves as an "infinitely thin skin". (This comment is also valid for the spinning drop tensiometer). For such reasons, a method of breakoff detection independent of interface electrical properties was desirable. Monitoring the pressure above the free surface internal to the contact piece appears to be a promising alternative.

Measurements of differential pressure in the order of 10^{-3} cm H₂O are possible with a capacitance pressure transducer. A voltage representing the pressure as a function of time/distance of contact circle translation may be put on a strip chart recorder. Pressure internal to the contact piece decreases as the interface is lowered (and the meniscus height grows); at

meniscus breakoff this pressure suddenly increases; with further lowering of the interface the pressure again decreases. A typical result is shown in the figure. The fluid statics for this situation has been completely analyzed.

Preliminary experiments with the pressure-sensitive breakoff detector have been carried out with an older model, borrowed, transducer. It appears to have slow internally generated thermal drift problems; this results in apparent pressure changes which could make data interpretation difficult over long times. A new transducer has been ordered and is expected to be available sometime during the next quarter (March 1 to May 31, 1977).

Also constructed during this quarter was a second spinning drop tensiometer. It features a completely exposed spin tube and continuously controllable rotation speed. It is hoped to observe low tension drops as they evolve into shapes not predicted by the theory of the instrument. It is furthermore hoped to relate such behavior to observations in the meniscal breakoff instrument, and to third phase development at the interface.

Synopsis of Activities, March 1, 1976 to February 28, 1977.

March to June 1976: Designed, constructed and tested Version III of the meniscal breakoff instrument.

July 1976: Completed in-house spinning drop tensiometer.

June to August 1976: Extensively tested the meniscal breakoff and spinning drop tensiometers with ordinary tension systems.

September to November 1976: Version III and spinning drop used with low tension systems. General agreement satisfactory but time history widely divergent.

December 1976: Designed a second spinning drop tensiometer.

January to February 1977: Developed and tested pressure-sensitive breakoff detector.

March 1977: Continuing to test and modify pressure-sensitive breakoff detector. Completed shop work on second spinning drop instrument.

MENISCAL BREAKOFF DETECTION BY MEASUREMENT OF SMALL PRESSURE CHANGES

1. SCHEMATIC

2. TYPICAL RUN; OCTANE + .2% WITCO TRS 10-80 SOLUTION, NOT EQUIL.

h : DISTANCE THE SPECIMEN CONTAINER MOVES DOWN.

$$\Delta P = P_{atm.} - P_2, \text{ WHERE } P_2 \text{ IS THE PRESSURE INSIDE THE CYLINDRIC CONTACT PIECE.}$$