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**SCALE-UP OF MISCIBLE FLOOD PROCESSES FOR
HETEROGENEOUS RESERVOIRS**

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Introduction

The current project is a systematic research effort aimed at quantifying relationships between process mechanisms that can lead to improved recovery from gas injection processes performed in heterogeneous Class 1 and Class 2 reservoirs. It will provide a rational basis for the design of displacement processes that take advantage of crossflow due to capillary, gravity and viscous forces to offset partially the adverse effects of heterogeneity. In effect, the high permeability zones are used to deliver fluid by crossflow to zones that would otherwise be flooded only very slowly. Thus, the research effort is divided into five areas:

- Development of miscibility in multicomponent systems
- Design estimates for nearly miscible displacements
- Design of miscible floods for fractured reservoirs
- Compositional flow visualization experiments
- Simulation of near-miscible flow in heterogeneous systems

The status of the research effort in each area is reviewed briefly in the following section.

Project Status

• Development of Miscibility in Multicomponent Systems

In this area, we have made significant progress in creating a systematic theory of miscibility development in multicomponent systems. Ph.D Student, Yun Wang, has developed a closed-form mathematical representation of the solutions for two-phase flow of three- and four-component systems with constant equilibrium ratios (K -values). Under the assumption of constant K -values, the solution is shown to have simple structure: all the ruled surfaces that solution path traverses are planes. The new analytical theory includes not only the explicit description of the key tie-line geometry but also a complete analytical representation of the ruled surfaces. The analytical approach allows us to construct the whole solution without resorting to numerical calculation which might introduce error. Although the constant K -value assumption is valid only when the system pressure is low, the theory gives us the first complete description of the solution behavior. Because the solution structure for constant K -values is similar in its essential details to that for two-phase flow of multicomponent systems, the analytical solution with estimated average K -values can be used as a guide to construct solutions for systems with variable K -values.

We have also made a significant step forward in extending the mathematical theory for four component systems to solve problems of eleven component systems. The details of this study is reported in the Result Section that follows.

• Design Estimates for Nearly Miscible Displacements

In this area, we have initiated a new effort to examine the effects of three-phase relative permeability behavior on the performance of gas injection processes in which all three phases

(gas, oil and water) move. Combining a newly developed mathematical theory of three-phase flow [6] and experimental measurements, we are in the process of evaluating the efficiencies of nearly miscible gas injection processes at reservoir scale to examine whether the high oil recoveries measured in laboratories are achievable in the fields. Initial results suggest that recovery efficiency depends strongly on the behavior of relative permeabilities. For example, even for systems with the same residual oil saturation, the amount of gas injected to recover most of the recoverable oil can vary from about one to hundreds of pore volumes, depending on the relative permeabilities used. This result highlights the need to investigate the factors that influence relative permeability behaviors, such as spreading coefficient, pore structures and wettability.

To investigate the effects of spreading coefficient on relative permeability behaviors, we have begun experiments to characterize a three-phase system with which we can control interfacial tensions at the three interfaces. The fluid systems under study are mixtures of iso-octane, normal-propanol, and brine solutions. By changing the salinity of the brine solution, we can vary the interfacial tensions and hence the spreading coefficient. Our primary measurements suggest that we can alter a system from initially non-spreading to spreading. This technique will enable us to conduct well-controlled three-phase displacement experiments.

- **Design of Miscible Floods for Fractured Reservoirs**

We have completed a set of experiments to investigate effects of spreading coefficient and reservoir heterogeneity on final oil recoveries by gravity drainage. Experiments have been carried out on water-wet sand columns using systems of water, hydrocarbons and air. Hexane (C_6), iso-octane (iC_8) and decane (C_{10}) have been used to vary the oil phase properties. Two types of sands were used to represent different heterogeneities. Measurements for hexane systems in the relatively homogeneous sand show that the residual oil saturations in the upper part of the column can be as low as 0.1 % of the pore volume, which is consistent with predictions from our vertical-equilibrium analysis[2]. However, for decane systems, which has a negative initial spreading coefficient, the residual oil saturations in the upper part of the heterogeneous sand are about 5.0 % of pore volume. Our measurements clearly demonstrate that residual oil saturations increase as the spreading coefficients become more negative, and increasing heterogeneity results in higher residual oil saturations for non-spreading systems. Investigations on the effects of wettability on residual oil saturations are also in progress.

Our high pressure drainage experiment continues producing new data from drainages of Means crude in the presence of CO_2 . We have obtained results from drainage of Means at pressures of 900, 1500, and 1700 psia on two sandstone cores of 100 and 500 mD. Our data show that increases in pressure (for the same temperature) result in increases in oil recovery, as a result, we believe, of the reduction in interfacial tension between gas and oil phases.

- **Flow Visualization Experiments**

We have continued to conduct flow visualization experiments. We have performed two-phase displacements of matched viscosity but different densities to investigate gravity effects without the influence of stabilizing or unstabilizing created by viscous forces. The observations from those experiments will be reproduced by the particle-tracking simulator.

Undergraduate student Bradley Peters is conducting experiments to investigate the scaling parameters for gravity and viscous forces in layered systems, by comparing the fluid distributions on two models of same heights but different lengths.

• Simulation of Flow in Heterogeneous Reservoirs

We have continued to investigate the streamline approach as a numerical alternative to conventional finite difference simulators to be used in predicting near-miscible gas injection in heterogeneous reservoirs. The streamline method has been generalized to include gravity, compositional effects and dispersion in three dimensions [1]. We have run multi-well tracer problems with one million blocks. More recently we have started looking at three-dimensional, first-contact miscible displacements with gravity. The ultimate goal of this project will be to test the streamline simulator with real field data and compare against conventional simulators. To this end, we are currently arranging to obtain field data from a couple of oil companies.

Darryl Fenwick, a Ph.D student, is finishing the construction of a three-dimensional network research simulator for three-phase flows and has been producing very interesting results[5]. He has found that spreading coefficients and saturation histories are among the most sensitive parameters in determining final oil recoveries from gas injections, which cannot be revealed by conventional capillary and relative permeability models. Combination of his network simulations and our laboratory measurements will enable us to obtain much better understanding relative permeability behaviors with changes in spreading coefficient, pore structures and wettability.

Research Results

In this section, we summarize results from a study of miscible gas displacement of multicomponent oils. The study was a joint effort of Prof. Russell T. Johns from the University of Texas at Austin and Prof. Orr (Only Prof. Orr was supported by DOE funds in this collaboration. The effort of Prof. Johns, who was the primary contributor of the multicomponent results, was not externally supported).

This work extends our four-component displacement theory to displacements of an oil with an arbitrary number of components by a single gas component. We first review key ideas from the three- and four-component theory. We then present a solution for a five-component displacement that demonstrates how multicomponent solutions are constructed. Next, we construct analytical solutions for displacements of a ten-component synthetic oil by CO_2 and compare the results to displacement experiments. Lastly, we show how to determine the MMP for any real oil displacement by a single-gas component.

Three-Component Theory

Johns[8] categorized phase behavior types and composition routes for both three- and four-component systems based on component volatilities of the oil and gas. For example, in ternary systems, there are only two basic types of two-phase phase behavior which depend solely on the volatility or K-value of the intermediate component (K_2). Fig. 1 illustrates these when the intermediate component has high volatility (HVI, $K_2 > 1$) and low volatility (LVI, $K_2 < 1$) and shows

Figure 1: Ternary phase-behavior classification based on component K -values. A) HVI: $K_1 > K_2 > 1, 1 > K_3$ and B) LVI: $K_1 > 1, 1 > K_2 > K_3$.

that the type of phase behavior determines the entire structure of the tie lines, eigenvector paths, and eigenvalues[8, 9]. Fig. 1 shows the direction the nontie-line eigenvalues must increase for both HVI and LVI. The direction reverses on opposite sides of the equivelocity curve (compositions where the phase flow velocities are equal).

Together with the eigenvalue paths and velocities, the specification of injection gas and initial oil compositions such as those shown in Fig. 2 allow for the features of the solution to be predicted and the displacement mechanism identified. Fig. 2 shows that there are only four types of solution features that can exist in a ternary displacement: two vaporizing and condensing solutions with and without a shock from the injection gas tie line to the oil tie line. The importance of this statement is that features of any ternary displacement can be predicted prior to a solution of the complex eigenvalue problem simply by recognizing the type of phase behavior and displacement mechanism. For example, in Fig. 2, type HVI phase behavior for a vaporizing mechanism must contain the following: 1) a leading downstream shock into the two-phase region beyond the equivelocity curve, 2) a continuous variation along the tie-line path (from D to C), 3) a switch at the umbilic composition (point C) to the nontie-line path where a continuous variation is taken (C to B), 4) a continuous variation along the gas tie line (B to A, this segment may be absent), and 5) a shock out of the two-phase region to the injection gas composition. For the same phase behavior type and a condensing displacement, however, the eigenvalue velocities along the nontie-line path increase upstream and a shock occurs that connects the oil tie line to the gas tie line (G to F). The reverse is true for type LVI phase behavior in that a continuous variation connects the two tie lines (Q to P) for a condensing drive and a shock for a vaporizing drive (L to K). Hence, Fig. 2 provides a visual method to predict the composition route without solving the eigenvalue problem. The patterns shown will be used extensively in the solution to displacements with more than three components.

Four-Component Theory

Four-component displacements simply consist of two back-to-back displacement segments that are similar to the ternary patterns[9]. Fig. 3A illustrates a typical composition route on a quaternary diagram, in which the gas and oil contain all four components. The composition route follows a "vertical" ruled surface from the initial oil composition and oil tie line, switches to a "horizontal"

Figure 2: Ternary composition routes for vaporizing and condensing displacements and A) HVI and B) LVI phase behavior. Shocks are shown by dashed lines and continuous variations along eigenvalue paths by solid lines.

ruled surface at the crossover tie line, and then follows along the horizontal surface until the gas tie line and injection gas composition is reached (a ruled surface is a surface composed of straight lines, tie lines in this case). The composition route is constrained to lie on these ruled surfaces as a result of applying the velocity constraint, entropy condition, continuity condition and material balances across shocks[8]. Each displacement along a ruled surface can be idealized as a pseudoternary displacement that is nearly planar in the quaternary diagram. The crossover tie line is aptly named as it is the only tie line that lies in both ruled surfaces and serves to connect successive pseudoternary displacements.

Features of four-component displacements (i.e. shocks or continuous variations along the ruled surfaces) can be determined by a simple application of ternary theory (Figs. 1 and 2) once the gas and oil compositions are specified. That is, each ruled surface can be treated as a HVI or LVI pseudoternary displacement with either a vaporizing or condensing displacement mechanism. For example, in Fig. 3A, the intermediate component C2 is condensed into the oil along the vertical surface. Component C3, however, is vaporized from the oil along the horizontal surface. Hence, Fig. 3A illustrates a combined condensing/vaporizing displacement where the leading downstream segment of the displacement is condensing and the trailing upstream segment, vaporizing[9].

If both components C1 and C2 have a K-value greater than one, the vertical surface can be idealized by HVI phase behavior with components C1, C2 and C3+. C3+ is a pseudocomponent of low volatility that consists of both components C3 and C4. Hence, a shock must occur upstream along the vertical surface from the oil tie line to the crossover tie line for a condensing displacement (see Fig. 2). The horizontal surface can be idealized by LVI phase behavior with the components

Figure 3: Typical composition route (A) and displacement mechanisms (B) for a quaternary displacement.

C1, C3, and C4. Because a vaporizing displacement occurs along the horizontal surface, a shock from the crossover tie line to the gas tie line must occur (see Fig. 2).

Fig. 3B illustrates the displacement mechanisms for quaternary systems. Because each successive pseudoternary solution can be either vaporizing or condensing, there are only four possible types of displacement mechanisms: pure condensing, condensing/vaporizing (C/V), vaporizing/condensing (V/C), and pure vaporizing. Examples of all of these displacement mechanisms can be found in the recent literature[9, 13, 4, 10, 8, 3].

Development of Miscibility

Miscibility in four-component displacements is developed when any of the key tie lines (i.e. the gas tie line, the oil tie line, or the crossover tie line) becomes a critical tie line. For displacements in which the crossover tie line controls the development of miscibility, the oil or gas composition does not have to lie outside of the region of tie-line extensions for a MCM flood, as it must for ternary displacements.

The displacement mechanism determines which key tie line controls the development of miscibility in quaternary displacements. For a purely vaporizing displacement, the oil tie line will become a critical tie line first as the pressure or gas enrichment is increased and will control the development of miscibility. For a purely condensing displacement, the opposite is true, and the gas tie line will control the development of miscibility.

For a C/V displacement, however, the situation is more complex. The crossover tie line which connects the condensing and vaporizing displacements is the tie line nearest the plait point, and it will control the development of miscibility in C/V displacements (see Johns et. al.[9] for

detailed proof of development of miscibility). For a V/C displacement, the opposite is true in that the crossover tie line is farthest from the plait point. Hence, in V/C displacements, either the oil or gas tie line will control the development of miscibility depending on their positions with respect to the plait point.

Five-Component Displacement

Next we consider a five-component analytical solution for a displacement of a four-component oil containing CH_4 , C_4 , C_{10} , and C_{20} by a fifth component (pure CO_2). The K-values calculated from the PREOS are ordered such that $K_{\text{CH}_4} > K_{\text{CO}_2} > 1.0$ and $1 > K_{\text{C}_{10}} > K_{\text{C}_{20}}$. This example is presented because it is the most complex analytical solution that can be visualized using quaternary diagrams and illustrates key ideas in the solution of multicomponent systems with more than five components.

Fig. 4 shows the phase behavior and analytical solution on two quaternary diagrams in which either $C_{\text{CH}_4} = 0.0$ or $C_{\text{CO}_2} = 0.0$ (see Johns and Orr [7] for equation-of-state parameter and additional details). Fig. 5 gives profiles. Fig. 5 also compares the analytical solutions to a numerical solution with 1000 grid blocks and $\Delta t_D/\Delta x_D = 0.1$. Excellent agreement between the two is obtained, although the numerical solution shows the effect of numerical dispersion.

Solution Construction

The difficulty in the construction of this solution is to find the key tie lines, compositions, and ruled surfaces that the composition route must traverse. Once these are specified, ternary theory applied along each ruled surface, determines whether or not a shock or a continuous variation from one key tie line to the next occurs.

The first ruled surface traversed is the one that connects the initial oil tie line to crossover tie-line 1. This ruled surface can be idealized by a pseudoternary displacement with the components CH_4 , CO_2 , and C_{4+} , where the injection gas is pure CO_2 and the oil is composed of CH_4 and C_{4+} . C_{4+} is a pseudocomponent that lumps the remaining heavy components. Ternary theory (Figs. 1 and 2) shows that the displacement along the first ruled surface is type HVI-condensing. Thus, a shock must occur along the ruled surface from the initial oil tie line to crossover tie-line 1 (from **B** in the upper quaternary diagram to **D** on the lower quaternary diagram, see Figs. 4 and 5) in order to satisfy the velocity constraint. At **D**, the lightest component, CH_4 , has been removed from the oil and displaced ahead of the less mobile liquid phase. Next, we use the key result that for a shock to occur within the two-phase region the tie-line extensions for tie lines upstream and downstream of the shock must intersect. Hence, we determine crossover tie-line 1 by finding the tie line on the $\text{CH}_4 = 0.0$ surface that intersects the oil tie line at X_1 . Once crossover tie-line 1 is found, we find composition **D** by constructing a tangent along crossover tie-line 1 to X_1 . Then, we determine the downstream composition (**B**) of the shock by solving the shock material balance equation. A continuous variation along the oil tie line does not occur because **B** lies between oil composition **O** and its tangent to the fractional flow curve on the oil tie line. Hence, the $\text{O} \rightarrow \text{B}$ shock is a genuine shock and a region of constant state exists at **B**.

The second ruled surface traversed by the composition route is the one in which the next most volatile component in the oil, C_4 , is displaced. Because CH_4 is no longer present, the displacement along this ruled surface can be idealized by a pseudoternary displacement with the

Figure 4: Quaternary diagrams for A) $CO_2=0$ and B) $CH_4=0$ showing the five-component composition route.

Figure 5: Composition and gas saturation profiles for the five-component displacement.

components CO_2 , C_4 , and C_{10+} in which the oil now contains all three components. Displacement by pure CO_2 along this ruled surface is type LVI-vaporizing, and a shock must occur from crossover tie-line 1 to crossover tie-line 2. Because a shock occurs, these two crossover tie lines must intersect (at $\mathbf{X}_2$) which allows for the location of crossover tie-line 2. Composition $\mathbf{E}$ is found again by the construction of a tangent along crossover tie-line 1 to $\mathbf{X}_2$. The upstream composition ($\mathbf{E}$) is also found by solving the shock material balance equation. A continuous variation exists between $\mathbf{D}$ and $\mathbf{E}$ along crossover tie-line 1.

The third ruled surface is easy to identify because it is exactly the $\text{CO}_2/\text{C}_{10}/\text{C}_{20}$ ternary plane (both CH_4 and C_4 are no longer present). The displacement by CO_2 along that ruled surface is also type LVI-vaporizing and a shock occurs from crossover tie-line 2 to the gas tie line. Again, those two tie lines must intersect (at $\mathbf{X}_3$), and the upstream composition ($\mathbf{G}$) can be found by solving the shock material balance equation. A continuous variation does not occur along the gas tie line because $\mathbf{F}$ lies between the tangent point to $\mathbf{X}_3$ and the injection gas composition $\mathbf{I}$. Hence, a region of constant state exists at $\mathbf{F}$.

Development of Miscibility

Analysis of the three successive pseudoternary displacements shows that the five-component displacement has a condensing/vaporizing/vaporizing mechanism, which after lumping the two upstream vaporizing segments, is similar to a C/V drive in quaternary displacements. The displacement along the first ruled surface primarily condenses CO_2 into the liquid phase, whereas the second and third ruled surfaces vaporize the intermediate components in the oil (C_4 and C_{10}). The K-values converge towards unity along the first ruled surface, and then continuously diverge from unity along the remaining ruled surfaces. Hence, the magnitude of the component K-values

on crossover tie-line 1 are nearer to unity than those of any other tie line of the displacement and crossover tie-line 1 controls the development of miscibility. If the pressure were increased enough that crossover tie-line 1 became a critical tie line, all shocks and continuous variations would have unit velocity and a MCM displacement would occur (see Orr et al.[13] and Johns et al.[9] for detailed mathematical proofs).

Eleven-Component Displacement

In this section, we examine the displacement of a synthetic oil by pure CO_2 and compare the results to the slim-tube experiments by Metcalfe and Yarborough[11]. Metcalfe and Yarborough performed three displacements at pressures of 1500 psia, 1700 psia, and 1900 psia, and at a temperature of 120 °F.

The phase behavior of the synthetic oil at 120 °F and 1500 psia is given in detail by Turek et. al.[15] Comparisons of the experimental PVT data with the PREOS (Pang-Robinson equation of state) show good agreement. For example, the experimental bubble point of the oil is 1479 psia and has a density of 0.486 gm/cc. Using the PREOS, we calculate a bubble point pressure of 1497 psia and a density of 0.487 gm/cc. The experimental dew point of a 95% CO_2 mixture with the synthetic oil is approximately 1430 psia at a density of 0.510 gm/cc. We calculate a dew point of 1500 psia with a density of 0.536 gm/cc. The viscosities of the oil and injection gas also agree well.

According to the PREOS, the volatilities of methane and carbon-dioxide are always greater than one with $K_{\text{CH}_4} > K_{\text{CO}_2}$. Ethane (K_{C_2}), however, can also be greater than one, depending on the displacement pressure. At pressures greater than approximately 1300 psia, K_{C_2} is generally less than one.

Solution Structure

The composition route traverses nine ruled surfaces that are connected by eight crossover tie lines. Along each ruled surface, a pseudoternary displacement takes place. As for the five-component displacement, the solution features along each ruled surface are determined *a priori* by using the ternary theory shown in Figs. 1 and 2.

The first ruled surface traversed by the composition route is idealized by a HVI pseudoternary system, $\text{CH}_4/\text{CO}_2/\text{C}_{2+}$, where C_{2+} is a pseudocomponent that consists of the remaining low volatility components. Hence, CO_2 is condensed into the oil along this ruled surface, and a shock must occur from the oil tie line to crossover tie line 1. Methane completely disappears at this shock and is displaced ahead.

The next ruled surface of the composition route is idealized by the components CO_2, C_2 , and C_{3+} . With a gas of pure CO_2 and an oil represented by the remaining two components, the pseudoternary displacement is LVI - vaporizing at 1500 psia, and a shock must occur from crossover tie-line 1 to crossover tie-line 2. Ethane is completely vaporized along this shock.

Because only heavy components of low volatility are now present, all subsequent pseudoternary displacements on the remaining seven ruled surfaces are type LVI - vaporizing. Hence, a displacement at 1500 psia will consist of one downstream condensing displacement followed by a sequence of upstream vaporizing shocks. As is discussed below, however, a displacement at 1500 psia is substantially above the MMP, and all shocks will approach unit velocity.

Figure 6: Tie-line lengths for the key crossover tie-line, the oil tie-line, and the gas tie-line. The MMP is found when crossover tie-line 1 has zero length at the critical locus.

Development of Miscibility

Miscibility is developed in this system when crossover tie-line 1 becomes a critical tie line. Because the downstream segment of the displacement is condensing and the remaining portions are vaporizing, crossover tie-line 1 is “nearer” to the critical point locus than any other tie line in the displacement. Fig. 7 illustrates this by a comparison of the composition tie-line lengths of crossover tie-line 1, gas tie line, and oil tie line. As is shown, the length of crossover tie-line 1 is substantially smaller than either the gas or oil tie line. Crossover tie-line 1 is also shorter than any of the other seven crossover tie lines. Furthermore, Fig. 7 shows that the length of crossover tie-line 1 becomes much shorter as the pressure is increased and eventually becomes a critical tie line at the MMP. The MMP for the synthetic oil displacement is estimated to be approximately 1350 psia. Our PREOS program could not converge as the critical locus was approached so an exact MMP could not be determined.

The MMP of 1350 psia leads to the result that the MMP is below the bubble point pressure. That is, an oil at the MMP is inside the two-phase region, and hence, a MCM flood can be obtained even when the oil has an initial gas saturation. The proof of this result is similar to that given by Johns et al.[9], which shows that all shocks and continuous variations have unit velocity at the MMP.

Discussion of the Experimental Results

Metcalfe and Yarborough[11] report normalized effluent concentrations for CO₂ displacements of the synthetic oil at pressures of 1500, 1700, and 1900 psia. They concluded that the 1700 psia flood was MCM and that the 1900 psia flood was first contact-miscible (FCM). We calculate a FCM pressure of approximately 1830 psia with the PREOS, which agrees with these conclusions.

Metcalfe and Yarborough also cautiously concluded that the flood at 1500 psia was immiscible because a mobile gas saturation was observed. They were uncertain, however, of their conclusion because “1500 psia is above the experimental single-contact critical pressure for mixtures of CO₂ with the synthetic oil” and “the normalized C₂ through C₆ fraction did not remain higher than the normalized C₇₊ fraction for some period of time ... which are more indicative of

simple mixing of CO₂ and oil". They also observed that the two-phase region disappeared before oil production ceased.

We show here that the slim-tube displacement at 1500 psia was MCM. Our result is consistent with the observed piston-like displacement at velocities near unity for all components including the C₇₊ fraction. Furthermore, our result is not inconsistent with the observed two-phase flow during the experimental displacement. The solutions given here are for dispersion-free flow and consider only phase-behavior effects. Displacements in porous media and slim-tube experiments, however, are anything but dispersion free. The effects of dispersion were considered by Johns et. al.[10] and Walsh and Orr[10]. They show that physical dispersion can cause two-phase flow in a 1D flow that is otherwise MCM. In addition, two-phase flow can be caused by viscous fingering, gravity segregation, and local permeability heterogeneity[14]. Hence, in real displacements some two-phase flow is inevitable even for floods that are MCM for one-dimensional dispersion-free flow.

Analytical Solution below the MMP

We present an analytical solution of the eleven-component displacement for a pressure (1200 psia) below the MMP. At 1200 psia, the oil has an initial gas saturation of 11.9%. The solution features for the displacement by CO₂ are similar to the one already described above, except that a shock does not occur along the second ruled surface from crossover tie-line 1 to crossover tie-line 2. Instead, a continuous variation occurs between these two tie lines along a nontie-line path that is principally directed towards decreasing C₂ concentrations. A continuous variation occurs because ethane now has a K-value greater than one at a pressure of 1200 psia, and the velocity constraint is no longer violated. That is, the pseudoternary displacement along the second ruled surface is now HVI - vaporizing instead of LVI - vaporizing. The composition profiles are given in Fig. 8. Fig. 8 shows good agreement between the analytical and numerical solution with 500 grid blocks and $\Delta t_D / \Delta x_D = 0.1$.

MCM Displacement of Real Oils

Real oils may consist of hundreds of components. Many of these components are heavy components with K-values less than one at field pressures and temperatures. Injection gases may consist of up to approximately 10 components. Gas components usually have high volatility, although heavier components can be used to enrich the gas. Components that may have K-values greater than one are typically H₂S, N₂, CO₂, CH₄, C₂, and possibly C₃.

We consider here only displacements by a single gas component, although the theory is similar for multicomponent gas injections[8]. To determine the MMP, the following procedure can be used:

1. Order the oil components by their K-values at some representative pressure with the highest volatility components first ($K_1^o, K_2^o, \dots, K_{n_c}^o$). Count the number of components, n_k , with K-values greater than the K-value of the injection gas.
2. Select the highest K-value component in the oil (K_1^o) and lump the remaining oil components into one pseudocomponent. Determine an average K-value for the pseudocomponent (K_{2+}^o) based on the molar compositions of each component, for example, using the Newley and

Figure 7: Composition and gas saturation profiles for the eleven-component displacement. The y-axis scale varies depending on the initial component concentration.

Merill[12] approach if needed. Usually, the pseudocomponent has a K-value much lower than one because it consists of mostly heavier components and a detailed calculation is not needed.

3. Determine the type of pseudoternary displacement along the ruled surface using the two "oil" components selected in step 2 and the injection gas component. Use Figs. 1 and 2 to predict if a shock occurs along the ruled surface or if a continuous variation is required.
4. Repeat steps 2 and 3 for the next $n_k - 1$ ruled surfaces, using the next highest K-value component in the oil and lumping the remaining oil components. All $n_c - 2$ ruled surfaces of the composition route do not need to be found for the MMP determination unless a full analytical solution is required because the remaining pseudoternary displacements will be vaporizing.
5. Order the pseudoternary displacement types from downstream to upstream. Determine which key tie line controls the development of miscibility by comparing the displacement types and finding the key tie line with the lowest expected K-values. K-values converge towards unity from downstream to upstream in condensing drives, but diverge in vaporizing drives.
6. Quantitatively identify the key tie line that controls the development of miscibility by locating all downstream key tie lines beginning with the oil tie line. If a shock occurs from one key tie line to the next (across a ruled surface), the upstream key tie line can be found by the important result that the downstream and upstream tie-line extensions must intersect[8, 9]. If a continuous variation occurs, then the upstream key tie line is found by following the nontie-line path in the principal direction that decreases the intermediate component of that pseudoternary displacement to zero concentration.
7. Once the key tie line that controls miscibility is found, slowly increase or decrease the pressure until that key tie line becomes a critical tie line. The pressure at which that key tie line becomes a critical tie line is the MMP.

Displacements of real oils that contain only components CH_4 , C_2 , and heavier, by pure CO_2 will always have one downstream condensing displacement followed by a sequence of upstream vaporizing drives. The most downstream crossover tie line will control the development of miscibility for such systems.

For displacements of the same real oils by pure N_2 or CH_4 , the displacement will be purely vaporizing and the oil tie line will control the development of miscibility. The oil tie line controls miscibility because the most downstream pseudoternary displacement is now HVI - vaporizing, instead of HVI - condensing as for displacements by pure CO_2 .

If the oil contains additional volatile components, such as N_2 or H_2S , one must follow the procedure given above to determine which key tie line controls the development of miscibility. It is likely, however, that for displacements of most real oil compositions by pure N_2 , those displacements will be purely vaporizing and miscibility will be controlled by the oil tie line.

Conclusions

Analytical solutions for five and eleven-component displacements by a single gas component show that:

- A multicontact miscible displacement (MCM) can occur even when the oil contains an initial gas saturation.
- For CO₂ displacements of real oils that contain only CH₄, C₂, and heavier components, the most downstream crossover tie line will control the development of miscibility, not the oil or injection gas tie line. For displacements of the same real oil by pure N₂ or CH₄, the oil tie line controls miscibility.
- The displacement mechanism for CO₂ displacements of a real oil that contain only CH₄, C₂, and heavier components will be both condensing and vaporizing (C/V) with a condensing downstream displacement. Displacements by pure N₂ or CH₄ of the same real oil will be purely vaporizing. The sequence of displacement mechanisms determines which key tie line controls the development of miscibility.
- The MMP can be estimated using the procedure outlined in this paper for displacement of a multicomponent oil by a single gas component.
- Multicomponent composition routes can be found using the idea of successive pseudoternary displacements along ruled surfaces.

References

- [1] Blunt, M. J. Liu, K. and Thiele, M. R.: "A Generalized Streamline Method to Predict Reservoir Flow," (May 1991) 8th European Symposium on Improved Oil Recovery, Austria.
- [2] Blunt, M.J., Zhou, D., and Fenwick, D.H.: "Three Phase Flow and Gravity Drainage in Porous Media," in press, *Transport in Porous Media* (1995).
- [3] Dindoruk, B.: *Analytical Theory of Multiphase, Multicomponent Displacement in Porous Media*, PhD dissertation, Stanford University, Stanford, CA (1992).
- [4] Dindoruk, B., Johns, R.T. and Orr, F.M., Jr.: "Analytical Solution for Four-Component Gas Displacements with Volume Change on Mixing," (June 1992) Third European Conference on the Mathematics of Oil Recovery, Delft, Holland.
- [5] Fenwick, D. H. and Blunt, M. J.: "Pore Level Modelling of Three-Phase Flow in Porous Media," (May 1991) 8th European Symposium on Improved Oil Recovery, Austria.
- [6] Guzman, R. E.: *Mathematics of Three-Phase Flow*, PhD dissertation, Stanford University, Stanford, CA (1995).
- [7] Johns, R. and Orr, F. M., Jr. : "Miscible Gas Displacement of Multicomponent Oils," (October 1995) paper SPE 30798 to be presented at the 1995 SPE Annual Technical Conference and Exhibition, Houston, TX.

- [8] Johns, R.T.: *Analytical Theory of Multicomponent Gas Drives With Two-Phase Mass Transfer*, PhD dissertation, Stanford University, Stanford, CA (1992).
- [9] Johns, R.T., Dindoruk, B., and Orr, F.M. Jr.: "Analytical Theory of Combined Condensing/Vaporizing Gas Drives," *SPE Advanced Technology Series* (1993) 1, No. 2, 7-16.
- [10] Johns, R.T., Fayers, F.J., and Orr, F.M. Jr.: "Effect of Gas Enrichment and Dispersion on Nearly Miscible Displacements in Condensing/Vaporizing Drives," *SPE Advanced Technology Series* (1993) 2, No. 2, 26-34.
- [11] Metcalfe, R.S. and Yarborough, L.: "The Effect of Phase Equilibria on the CO₂ Displacement Mechanism," *Soc. Pet. Eng. J.* (August 1979) 242-252.
- [12] Newley, T.M.J. and Merrill R.C. Jr.: "Pseudocomponent Selection for Compositional Simulation," *Soc. Pet. Eng. Res. Eng.* (November 1991) 6, No. 4, 490-496.
- [13] Orr, F.M. Jr., Johns, R.T., and Dindoruk, B.: "Development of Miscibility in Four-Component CO₂ Floods," *Soc. Pet. Eng. Res. Eng.* (1993) 8, 135-142.
- [14] Pande, K.K. and Orr, F.M., Jr.: "Interaction of Phase Behavior, Reservoir Heterogeneity and and Crossflow in CO₂ Floods," paper SPE 19668 presented at the 1989 SPE Annual Technical Conference and Exhibition, San Antonio, TX, October 8-11.
- [15] Turek, E.A., Metcalfe, R.S., and Yarborough, L.: "Phase Equilibria in Carbon Dioxide - Multicomponent Hydrocarbon Systems: Experimental Data and an Improved Prediction Technique," *Soc. Pet. Eng. J.* (June 1984) 308-324.

United States Government

Department of Energy
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memorandum

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The attached technical/topical report has been submitted by the contractor/recipient and requires your review and approval. Review should be completed within 15 calendar days of the date of this memo.

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