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A Combined Condensing/Vaporizing Mechanism in the Displacement of Oil by Enriched Gases

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ABSTRACT

Experimental observations, combined with equation-of-state predictions, indicate that a combined condensing/vaporizing-gas drive mechanism, rather than the traditionally believed condensing-gas drive mechanism, may be responsible for displacements of reservoir oil by enriched gases. Apparent minimum miscibility pressures and minimum solvent enrichments are observed with this mechanism, even though true miscibility is probably not developed.

INTRODUCTION

Pseudoternary diagrams were first used to explain the mechanisms of oil displacement by vaporizing-gas drives[1] and condensing-gas drives[2] more than 30 years ago. Since then, all displacements of oil by injected gases have been categorized as either immiscible, multicontact miscible, or first contact miscible, with the multicontact miscible displacements further divided into either condensing-gas drive processes or vaporizing-gas drive processes.[3] Soon after those displacement mechanisms were proposed, Benham et al.[4] proposed a method of predicting minimum miscibility conditions by constructing pseudoternary diagrams and estimating the placements of the critical tielines. That method has been in use ever since, although it has been updated slightly in recent years by the use of equations-of-state to generate the pseudoternary diagrams.[5-8]

The problem with using pseudoternary diagrams to explain or predict multicontact miscibility is that they rigorously apply only to true ternary systems. It has generally been assumed in the past that pseudoternary diagrams, while perhaps not exact, at

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References and illustrations at end of paper.

least capture the basic phase behavior mechanisms of reservoir fluid displacements. That assumption may not always be justified.

For a three-component hydrocarbon system, when a rich injection gas displaces an oil that is relatively lean in the intermediate component, it is by a mechanism that is called a condensing-gas drive. In this process, which has been well described elsewhere,[3-7] the oil near the injection point is enriched by repeated contacts with the injection gas. The intermediate component in the gas condenses into the oil, moving its composition toward the critical point on the phase envelope. Eventually, if the gas is rich enough, i.e., if its composition lies on the single phase side of the extended critical tieline, the oil becomes so enriched with the intermediate component that it becomes miscible with the gas. Since the miscible zone moves with the velocity of the injection gas, the oil is completely displaced. This process can be easily visualized with the aid of a ternary diagram. The ternary diagram in Figure 1 was generated by simulating a methane-butane-decane multicontact process at minimum miscibility conditions with the Peng-Robinson equation-of-state.

Phase envelopes for multicomponent reservoir fluids can be generated by simply mixing the fluid with light and intermediate components in various proportions, flashing the resulting mixtures, and measuring the equilibrium compositions. Since these phase envelopes, when projected onto pseudoternary diagrams, look very similar to the phase envelopes for ternary hydrocarbon systems, it has been assumed that the displacement of these multicomponent oils by enriched gases will be by the same condensing-gas drive mechanism that applies to the ternary system. That assumption, however, does not take into account the changes in the distribution of components, and hence the changes in the

projected phase envelope, that occur during a multicontact displacement process for the multicomponent system. Stalkup,[3,9] for example, observed that enriched-gas, multicontact phase behavior could be too complicated to explain with the classical condensing-gas drive mechanism and conventional pseudoternary diagrams.

This paper will provide experimental evidence showing that displacements of a real, multicomponent, reservoir fluid by enriched gases, which were 98% efficient and by all indications appeared to have developed miscibility, could not have involved either the condensing-gas drive mechanism or the vaporizing-gas drive mechanism alone. Instead, a combined condensing/vaporizing mechanism will be proposed to explain the efficient displacements. With this mechanism, a region of near miscibility is developed and propagated, but it is possible that a point of true miscibility is never actually developed. Furthermore, it will be argued that the true condensing-gas drive mechanism may rarely, if ever, occur in displacements of real reservoir fluids by enriched gases.

CONDENSING/VAPORIZING MECHANISM

The easiest way to understand the condensing/vaporizing mechanism is to consider an oil/gas system composed of essentially four groups of components. The first group consists of the lean components, such as methane, nitrogen, and carbon dioxide, which usually have equilibrium K-values greater than one. The second group consists of the light intermediate components, such as ethane, propane, and butane, which are the enriching components present in the injection gas. The third group contains the middle intermediates which are present in the oil but not significantly present in the injection gas. These are components that can be vaporized from the oil. The lightest component in this group typically ranges from butane to decane, depending on the injection gas composition. The heaviest component in this group cannot be defined precisely, but it might be around C_{30}. The fourth group consists of everything else, i.e., those heavy components in the oil which are very difficult to vaporize.

When the enriched gas comes into contact with the oil, the light intermediates condense from the gas into the oil, making the oil lighter. The equilibrium gas is more mobile than the oil, so it moves on ahead and is replaced by fresh injection gas, from which more light intermediates condense, making the oil even lighter. If this kept occurring until the oil was light enough to be miscible with the injection gas, it would constitute the condensing-gas drive mechanism. However, this is unlikely to occur with a real reservoir oil. As the light intermediates are condensing from the injection gas into the oil, the middle intermediates are being stripped from the oil into the gas. Since the injection gas contains none of these middle intermediates, they cannot be replenished in the oil. After a few contacts between the oil and the injection gas, the oil becomes essentially saturated in the light intermediates, but it continues to lose the middle intermediates which are

stripped out and carried on ahead by the mobile gas phase. The light intermediates of the injection gas cannot substitute for the middle intermediates the oil is losing. So after the first few contacts make the oil lighter, by net condensation of intermediates, subsequent contacts make the oil heavier, by net vaporization of intermediates. Once this begins to occur, the oil no longer has a chance of becoming miscible with the gas. Ultimately, all of the middle intermediates are removed and the residual oil will be very heavy, containing only the heaviest, nonvolatile fraction and the components present in the injection gas.

If the mechanism stopped there, a considerable amount of oil would remain unrecovered. However, there are further steps to the mechanism. Consider the oil in place slightly downstream from the injection point. The first gas it will see will not be the injection gas, but equilibrium gas. This relatively lean gas will be essentially injection gas that has lost most of its light intermediates and picked up a very small amount of middle intermediates. There will be very little mass transfer between this gas and the fresh oil. The gas that follows, however, will be richer. Eventually, the gas that comes through will be gas that has passed over oil that was saturated in the light intermediates. Therefore, this gas will have about the same amount of light intermediates as the injection gas. But it will also contain a small amount of middle intermediates that it stripped from the oil over which it passed. Thus, it will actually be a little richer than the original injection gas. The oil that sees this gas will receive slightly more condensible intermediates than did the oil just upstream. Before the vaporization process takes over and again makes it heavier, this oil will become slightly lighter than the upstream oil had become.

The above process continues farther downstream. The farther downstream, the richer the gas that eventually comes through, because it will have passed over an increasing amount of residual oil, allowing it to pick up increasing amounts of middle intermediates. This is beginning to sound like the vaporizing-gas drive mechanism, in which a lean injection gas passes over an oil rich in intermediates, vaporizing the intermediates, becoming richer and richer, until it becomes rich enough to be miscible with the original oil. There is a big difference, however. The gas in the condensing/vaporizing mechanism does not become rich enough to be miscible with the original oil. The original oil does not have to be rich in intermediates, nor does it even have to be undersaturated, both of which are necessary conditions for developing a vaporizing-gas drive mechanism. Instead, the gas develops only enough richness by the vaporization part of the mechanism so that it nearly generates a condensing-gas drive mechanism with the original oil. The intermediates that were originally present in the gas, plus those that were stripped from the oil, condense when the gas encounters fresh oil downstream. This condensation proceeds in a manner very much like the condensing-gas drive mechanism. A sharp transition zone develops and propagates, and multicontact miscibility is almost achieved before the condensation process reverts to the

vaporization process. The vaporization results in a trail of residual oil being left behind the moving transition zone, although the saturation level of the residual can be very small. The residual oil supplies subsequent gas with the middle intermediates necessary to continue the propagation of the transition zone. The intermediates are vaporized from the residual oil, carried upstream into and beyond the transition zone, condensed there, and again become part of the residual oil after the transition zone has passed.

The condensing region is at the leading edge of the enriched-gas displacement. The vaporizing region, with a small saturation of residual oil, is at the trailing end. In between is the sharp, two-phase transition zone, the two phases of which are almost, but not quite, miscible. The propagation of the sharp transition zone results in a very efficient, "apparently miscible" displacement, even though miscibility is not actually developed (except possibly, and only speculatively, as the displacement front travels to infinite distances, relative to dispersion length scales, downstream of the injection point). The sharpness of the transition zone deteriorates rapidly as either the pressure or the enrichment of the injection gas falls below some critical value, resulting in the reduced displacement efficiencies typical of immiscible displacements.

The above description of the condensing/vaporizing mechanism will be clarified later, when simulation results, illustrating the important features of the mechanism, are presented.

EXPERIMENTAL EVIDENCE

The composition of Reservoir Fluid A is given in Table 1. The C_{7+} fraction of this fluid had a molecular weight of about 275. The bubble point was about 3800 psig at the reservoir temperature of $185^{\circ}F$. Table 1 also gives the composition of Solvent A, which would be available for flooding the reservoir. A series of slimtube displacement experiments showed this solvent to have an apparent minimum miscibility pressure (MMP) of about 2200 psig for a 1500 psig depleted sample of Reservoir Fluid A. Figure 2 shows the experimental volume-fraction of oil recovered after 1.2 PV of gas injection as a function of displacement pressure. For each displacement experiment, a 60-ft., 0.25-in. i.d., sand-packed tube was filled with a sample of Reservoir Fluid A which had been depleted to 1500 psig. The back-pressure regulator was set to the desired displacement pressure and solvent was injected at the rate of about 0.04 pore volumes (PV) per hour. These conditions ensured low pressure drops and low dispersion. The effluent was separated at room conditions into liquid and gas phases and measurements included oil and gas volumes and gas compositions.

Since Solvent A had an apparent MMP much lower than the lowest anticipated reservoir pressure, it could be diluted significantly with methane. Additional sets of slimtube displacements were performed to determine how much dilution could be tolerated at higher displacement pressures. The first of these

displacements were performed at 3100 psig with a sample of Reservoir Fluid A which had been depleted to 3000 psig. Figure 3 shows the experimental recoveries for various levels of dilution of Solvent A by methane. A dilution level of zero means the injectant was pure Solvent A while a dilution level of one means the injectant was pure methane. The apparent minimum miscibility enrichment at 3100 psig was about 80% Solvent A, 20% methane. In other words, a solvent composed of 80% Solvent A and 20% methane had an apparent MMP of about 3100 psig. Additional slimtube displacements were performed at 3400 psig with the reservoir fluid depleted to 3300 psig. The results from these displacements indicated a minimum enrichment at 3400 psig of about 77% Solvent A, 23% methane.

Since these were enriched-gas displacements of a fairly heavy reservoir fluid, the displacements had been anticipated to be by a condensing-gas drive mechanism. However, preliminary simulations, using the Peng-Robinson equation-of-state and a fully compositional slimtube simulator, showed a condensing-gas drive mechanism only if the C_{7+} fraction of the oil was treated as a single pseudo-component. If the C_{7+} fraction of the oil was more realistically divided into several pseudocomponents, the simulations always showed a condensing/-vaporizing type of displacement mechanism. It was not immediately clear whether the displacements truly were by the condensing/vaporizing mechanism or whether they were simply by a condensing-gas drive mechanism that the equation-of-state was unable to model. Therefore, a series of single cell, multiple contact experiments was designed to distinguish between the two mechanisms.

The multiple contact experiments were conducted as follows: (a) a sample of reservoir fluid was loaded into a pressure-volume-temperature (PVT) cell, (b) a sample of injectant was introduced, (c) the cell was allowed to equilibrate at the desired pressure, (d) phase volumes were measured, (e) the equilibrium gas phase was removed and analyzed, (f) a small sample of equilibrium liquid phase was removed and analyzed, and (g) the procedure was returned to step b. Typically, about seven stages, or contacts, were performed during each experiment.

If the mechanism were a condensing-gas drive, such a multiple contact experiment would cause the equilibrium liquid phase density to decrease monotonically with the number of stages, the equilibrium gas phase density to increase monotonically, and the equilibrium K-values to change monotonically toward unity. If the pressure were above the MMP of the injectant and enough contacts were made, the injectant would eventually become first-contact miscible with the liquid in the cell. This would be evidenced by the liquid and gas phase densities converging to the same value and the K-values all becoming 1.

On the other hand, if the mechanism is of the condensing/vaporizing type, the multiple contact experiment will cause the equilibrium liquid phase density to decrease for the first few contacts, reach a minimum, and then increase. The equilibrium gas phase density will increase at first, reach a maximum, and then decrease. The K-values

will initially converge toward unity, but will then reach extrema and begin to diverge away from unity.

The first multiple contact experiment was performed at reservoir temperature and a pressure of 3100 psig. The injectant gas was a mixture of 84% Solvent A and 16% methane. Since this is richer than the 80/20 solvent, its apparent MMP would be lower than 3100 psig. The volume of solvent injected at each stage was nominally one-third the volume of the liquid remaining in the cell. The results of this experiment are shown in Figures 4 and 5. Also shown in these figures are the results from the equation-of-state, which was tuned to match these and other data. The liquid density definitely seems to have gone through a minimum. The gas phase density may have gone through a maximum or it may have reached an asymptotic limit; the scatter in the data precludes making a judgement. Likewise, it is not clear whether the K-values went through extrema or simply reached asymptotes. In either case, miscibility was certainly not achieved, and would not have been achieved with additional contacts. The K-values were not converging toward unity, nor were the phase densities approaching each other, even though the pressure of the experiment was above the apparent MMP of the solvent. This experiment did not support the hypothesis of the condensing-gas drive mechanism. It appears to support the condensing/-vaporizing mechanism, although not enough contacts were made to clearly show the extrema in the gas density and K-values.

The multicontact experiment was then repeated at 3600 psig, everything else held constant. This pressure was more than 500 psi above the apparent MMP of the solvent. The results are shown in Figures 6 and 7. This time, all results are clearly consistent with the condensing/vaporizing mechanism and inconsistent with the condensing-gas drive mechanism. The densities and the K-values all go through extrema. Note also that this single-cell experiment did not come at all close to producing miscibility, even 500 psi above the apparent MMP of the solvent. That is completely inconsistent with the condensing-gas drive mechanism but not inconsistent with the condensing/vaporizing mechanism, which predicts that near-miscibility will be produced only at some distance downstream of the injection point and not at the injection point itself.

EQUATION-OF-STATE PREDICTIONS

The multicontact experiments established that the displacement of Reservoir Fluid A by the available enriched-gas solvents would not be by a condensing-gas drive mechanism. Instead, they showed behavior consistent with the proposed condensing/vaporizing mechanism. To gain further understanding about the mechanism, one must resort to numerical simulation, using a tuned equation-of-state. It is recognized that no existing equation-of-state is perfect and that numerical displacement simulations are prone to numerous assumptions and discretization problems. However, it is felt that the results presented below are qualitatively valid and even of reasonable quantitative accuracy.

The Peng-Robinson equation-of-state, modified with a third (volumetric shift) parameter for each component,[10] was used for all the simulations. The fluid characterization employed 12 components, including 6 pseudocomponents for the C_{7+} fraction. The heaviest pseudocomponent represented the C_{30+} fraction.

Figures 4 through 7 already have shown the accuracy of the equation-of-state in matching some of the data. A vast amount of other data went into the development of the characterization. In general, they were all matched with about the same accuracy. The match for only one other set of experiments will be shown here, however, and then only because it is particularly relevant. The experiments were constant composition expansions conducted during a swelling test. The reservoir fluid was mixed in various proportions with Solvent A and a constant composition expansion was performed for each mixture. The liquid dropout was measured as a function of pressure during each expansion. The reason this experiment is relevant is because the liquid saturations were measured on both the bubble point and dew point sides of a critical mixture. The matching of these data, as shown in Figure 8, allowed more confidence in the equation-of-state's accuracy near critical points.

Data from the slimtube displacement experiments were not employed in developing the fluid characterization. These displacements were predicted independently after the characterization was developed. A few comments about the simulations are noted here. The equation-of-state was solved by the General Dominant Eigenvalue Method,[11,12] which provides efficient, accurate solutions even when all K-values are within 0.02 of unity (very close to a critical point). The simulated pressure drop across the slimtube was kept negligible. The capillary pressure between oil and gas was zero. The time steps were explicit and fixed, with one-tenth of a grid block volume of solvent injected per time step. Explicit mobilities were used. Two-point upstream weighting on the fluxes was used as much as possible without introducing overshoot. Physical dispersion was not modeled. The relative permeabilities were chosen to match the clearly immiscible displacement results as closely as possible. Sensitivity studies showed that the relative permeabilities did not affect the predictions of the effective minimum miscibility conditions; they only affected the recoveries for the obviously immiscible displacements.

Figure 9 shows some typical slimtube simulation results showing predicted recovery as a function of the dilution of Solvent A with methane. Results were similar for the simulations of other sets of slimtube experiments, both of this type and of the more usual, recovery versus pressure type. The simulations were performed with 25, 50, 100, and 200 grid blocks; the results were also extrapolated to an infinite number of grid blocks. Figure 9 shows that the experimental recoveries can be accurately predicted by the equation-of-state, but that a very large number of grid blocks are required. The reason is because the actual slimtube apparently exhibited very little physical dispersion. That meant that the length of each

mixing zone, or "theoretical plate," within the slimtube was very short. Each theoretical plate is modeled by roughly one grid block, therefore a large number of grid blocks is needed to model the entire slimtube. The purpose of this paper is not to delve into the problems of modeling physical dispersion and eliminating numerical dispersion. Better discussions of those problems can be found elsewhere.[13] The main objective here is to present evidence of the condensing/vaporizing-gas drive mechanism. Figure 9 shows that grid block size affects the quantitative slimtube predictions. Fortunately, the qualitative predictions, such as the displacement mechanism, are not affected by grid block size or the amount of physical or numerical dispersion (assuming that there is at least some physical mixing that prevents the gas from displacing the oil in a completely unmixed, piston-like manner). These qualitative results ae presented below.

For comparison purposes, a true condensing-gas drive displacement and a true vaporizing-gas drive displacement were simulated for the methane-butane-decane ternary system. Figure 10 shows the saturation, density, and K-value profiles within the slimtube during the condensing-gas drive displacement. One-half pore volume of solvent has been injected at a pressure just above its MMP. Figure 11 shows the same profiles for a vaporizing-gas drive. One-half pore volume of methane has been injected at a pressue just above the MMP of the original oil. Notice that miscibility is developed at the trailing edge of the two-phase transition zone during the condensing-gas drive and at the leading edge during the vaporizing-gas drive.

Figure 12 shows the saturation, density, and K-value profiles for a displacement by the condensing/vaporizing mechanism. These profiles, again at one-half pore volume of gas injected, were generated during the 200 grid block simulation of the displacement of a 3000 psig depleted sample of Reservoir Fluid A by Solvent A at a pressure of 3100 psig. As can be seen in Figures 2, 3, and 9, that solvent was significantly overenriched at that pressure, i.e., its apparent MMP was about 900 psi below the displacement pressure. Yet the simulations predict that true miscibility was not achieved. Instead, the simulations predict the development of a sharp, near-miscible transition zone. Upstream of the transition zone is the vaporizing zone, very similar to that of the vaporizing-gas drive. Downstream is the condensing zone, similar to that of the condensing-gas drive. The transition zone propagates down the tube, effectively displacing all but a small amount of heavy, residual oil. Table 2 gives the predicted gas, liquid, and overall compositions from the middle of the transition zone, where the fluid was closest to miscibility. By comparing this table with Table 1, it can be seen that the distribution of components has been significantly altered from that of the original Reservoir Fluid A. The near-miscible fluid is much richer in the middle intermediates. Those components were vaporized from the residual oil upstream and recondensed in the transition zone.

DISCUSSION

The condensing/vaporizing-gas drive mechanism has been explained, experimental evidence in its support has been presented, and some of its effects have been demonstrated by simulations. Those have been the major points of this paper. Some additional observations are made below, however.

The condensing/vaporizing mechanism does not seem to be unique to Reservoir Fluid A and Solvent A. Single-cell, multiple contact experiments have demonstrated the condensing/vaporizing mechanism for two other oil/solvent systems. Table 3 gives the compositions of Reservoir Fluid B and Solvent B, which were used in a multicontact experiment at $160°F$ and 3200 psig. Reservoir Fluid B has a C_{7+} molecular weight of about 325. Table 4 gives the compositions of Reservoir Fluid C and Solvent C. These were used in a multicontact experiment at $205°F$ and 3000 psig. The C_{7+} molecular weight of Reservoir Fluid C is about 199. In both experiments, the results precluded the condensing-gas drive mechanism but were consistent with the condensing/vaporizing mechanism. Reservoir Fluids A, B, and C are quite dissimilar, especially in the C_{7+} properties, and Solvents A, B, and C are very much different. Yet all three systems showed the condensing/vaporizing mechanism rather than the condensing-gas drive mechanism.

There is also evidence of the condensing/vaporizing mechanism in the literature. Stalkup[9] observed phase behavior typical of the combined mechanism during an enriched-gas, multicontact experiment. He noted that the equilibrium phase compositions seemed to converge for the first contact but diverge on subsequent contacts. Shelton and Yarborough[14] described some multicontact experiments and core flood experiments which seem to have exhibited the combined mechanism, although they speculated that their observations were the results of complex multiple-phase behavior. Their multicontact experiments showed the liquid and gas phase properties to converge for the first contact or two and to diverge on subsequent contacts. And during the core floods, the molecular weight of the produced oil began decreasing after gas breakthrough, but then went through a minimum and began increasing. The core was flushed after the flood and a significant amount of residual oil, much heavier than the original oil, was found. These observations are completely inconsistent with the condensing-gas drive mechanism but are exactly to be expected from the condensing/vaporizing mechanism.

Numerical experiments seem to indicate that the condensing/vaporizing mechanism is much more common than the condensing-gas drive. The combined mechanism can be observed with oils containing as few as four components, although it is most pronounced with realistic reservoir fluid characterizations. The condensing mechanism is usually observed only when all of the middle intermediate and heavy components of the oil (e.g., the entire C_{7+} fraction) are lumped into a single pseudocomponent. Of course, such a lumping scheme is very unrealistic and makes it impossible for the equation-of-state to accurately predict any but the simplest PVT experiment. Given a reasonable fluid characteriza-

tion, almost any solvent that would be considered as a rich gas will produce the condensing/vaporizing mechanism. The CO_2 content of the gas seems immaterial. The identities and amounts of the enriching components (as long as the solvent doesn't become first-contact miscible) also seem unimportant, although they affect the apparent MMP of the solvent. The term "apparent MMP" is used here because the simulations suggest that true miscibility (i.e., a critical or supercritical composition) may never be produced by the combined mechanism, even during displacements which recover nearly 100% of the oil and by all other definitions would have been called "miscible" displacements. This point is somewhat speculative and will have to be investigated further.

It remains to be seen whether the apparent MMP of a solvent can be easily predicted or correlated. It appears that slimtube simulations, with a good fluid characterization and a large enough number of grid blocks, can accurately predict apparent MMP's. But the characterization procedure and slimtube simulations can be rather time-consuming and costly. It would be desirable to at least bypass the simulations. So far, however, no satisfactory alternative has been found. The pseudoternary diagram approach, while perhaps still useful for vaporizing-gas drives and (the probably rare) condensing-gas drives, will not be reliable for the condensing/vaporizing mechanism. (This discussion applies only to purely predictive pseudoternary methods, and does not apply to correlations that were adjusted to match experimental data, even though they may have been based on pseudoternary theories.) Figure 13 shows the pseudoternary diagram that is produced by a multiple contacting process with Reservoir Fluid A and Solvent A at $185°F$ and 3100 psig (900 psi above the apparent MMP of this oil/solvent system). This figure looks nothing like the true ternary diagram in Figure 1 and the fact that this system will result in an apparently miscible displacement is not at all obvious. This points out how questionable it is to try predicting minimum miscibility conditions for an enriched-gas displacement process by using pseudoternary diagrams.

Other questions still to be answered include those concerning the condensing/vaporizing mechanism on a reservoir scale. On the laboratory scale, this mechanism can displace oil with nearly 100% efficiency. But how will the displacement efficiency be affected on the field scale by factors such as gravity, heterogeneity, dispersion, fingering, spatially and temporally varying pressures, slug sizes, WAG (water alternating gas) ratios, etc.? Will injectivity suffer because of the residual oil inherently left behind the transition zone? These questions may be more difficult to answer for the condensing/vaporizing mechanism than for either the condensing-gas drive or the vaporizing-gas drive mechanism, because it is essentially a combination of the other two.

CONCLUSIONS

Experimental data, backed by equation-of-state simulations, indicate that a combined, condensing/vaporizing-gas drive mechanism is responsible for several laboratory displacements of reservoir fluids by enriched gases. Those displacements could not have been by the traditionally accepted condensing-gas drive mechanism. In fact, simulations suggest that that mechanism may rarely occur in enriched-gas displacements of reservoir fluids.

Above an apparent minimum miscibility pressure, the condensing/vaporizing mechanism can generate displacements that are effectively miscible, although true miscibility may not actually be developed. These displacements are characterized by the development and propagation of a nearly miscible (but two phase) transition zone which is preceded by a zone of original oil in equilibrium with gas that has lost its condensible intermediates, and which leaves behind it a heavy, residual oil that has lost its vaporizable intermediates.

Pseudoternary diagrams cannot be used to explain or predict effectively miscible displacements of oil by enriched gases when the mechanism is the condensing/vaporizing-gas drive.

ACKNOWLEDGEMENTS

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Table 1

Compositions of Reservoir Fluid A and Solvent A

Component	Mole Fractions Reservoir Fluid A	Solvent A
CO_2	0.0699	0.2218
Methane	0.4146	0.2349
Ethane	0.0540	0.2350
Propane	0.0360	0.2745
Butanes	0.0245	0.0338
Pentanes	0.0173	
C_6-C_7	0.0411	
C_8-C_{10}	0.0781	
C_{11}-C_{14}	0.0716	
C_{15}-C_{19}	0.0635	
C_{20}-C_{29}	0.0586	
C_{30+}	0.0708	

Table 2

Calculated Compositions from Near-Miscible Region of Displacement of Reservoir Fluid A by Solvent A

Component	Mole Fractions Liquid	Gas	Overall
CO_2	0.1788	0.1899	0.1860
Methane	0.2237	0.2437	0.2368
Ethane	0.1913	0.1991	0.1963
Propane	0.2240	0.2249	0.2246
Butanes	0.0339	0.0330	0.0333
Pentanes	0.0058	0.0055	0.0056
C_6-C_7	0.0161	0.0143	0.0149
C_8-C_{10}	0.0332	0.0281	0.0299
C_{11}-C_{14}	0.0322	0.0254	0.0278
C_{15}-C_{19}	0.0251	0.0170	0.0198
C_{20}-C_{29}	0.0193	0.0116	0.0143
C_{30+}	0.0166	0.0075	0.0107

Table 3

Compositions of Reservoir Fluid B and Solvent B

Component	Mole Fractions Reservoir Fluid B	Solvent B
CO_2	0.0063	0.0004
Methane	0.4015	0.5694
Ethane	0.0514	0.1302
Propane	0.0325	0.1430
Butanes	0.0280	0.0916
Pentanes	0.0206	0.0460
C_6-C_7	0.0400	0.0194
C_8-C_{10}	0.0849	
C_{11}-C_{14}	0.0927	
C_{15}-C_{19}	0.0811	
C_{20}-C_{29}	0.0666	
C_{30+}	0.0944	

Table 4

Compositions of Reservoir Fluid C and Solvent C

Component	Mole Fractions Reservoir Fluid C	Solvent C
CO_2	0.0033	0.0004
Methane	0.4207	0.6025
Ethane	0.0597	0.0680
Propane	0.0371	0.2657
Butanes	0.0312	0.0322
Pentanes	0.0223	0.0169
C_6-C_7	0.0558	0.0143
C_8-C_{10}	0.1392	
C_{11}-C_{14}	0.0888	
C_{15}-C_{19}	0.0591	
C_{20}-C_{29}	0.0404	
C_{30+}	0.0424	

Fig. 3—Experimental slimtube recovery at 3,100 psig as a function of solvent dilution.

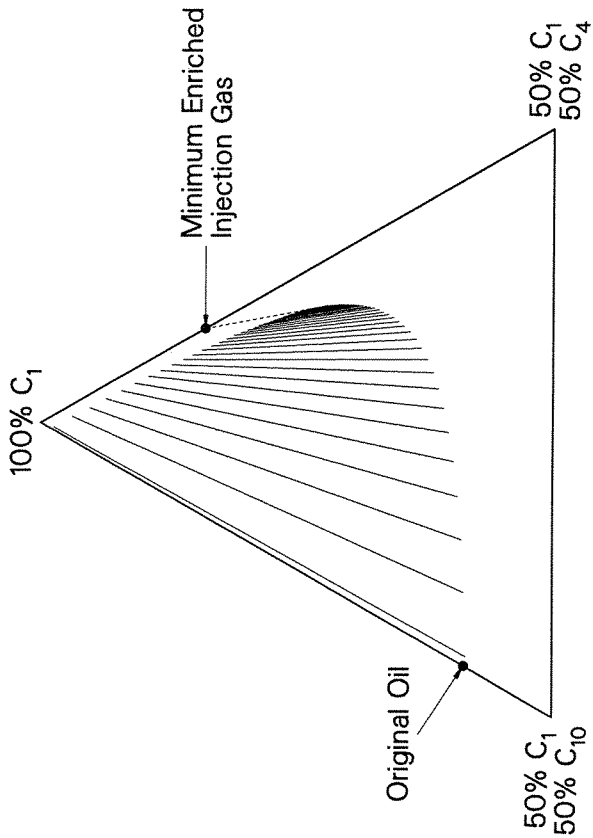Fig. 4—Experiment (symbols) and simulated (curves) densities from multicontact experiment at 3,100 psig.
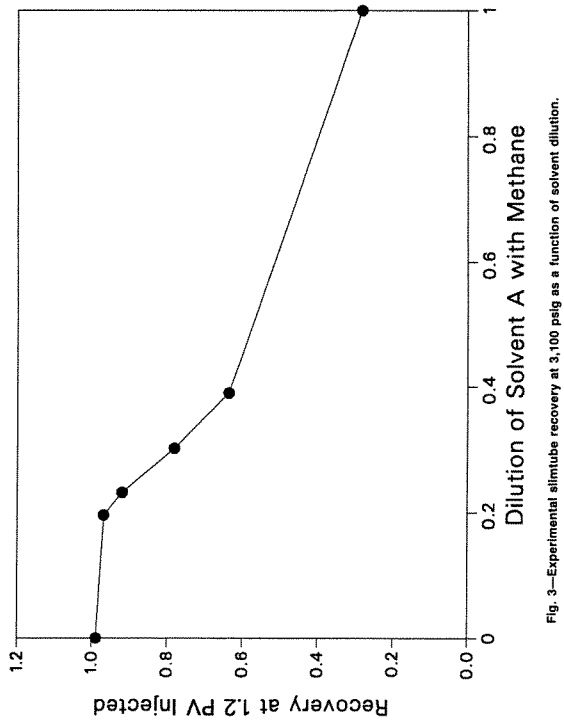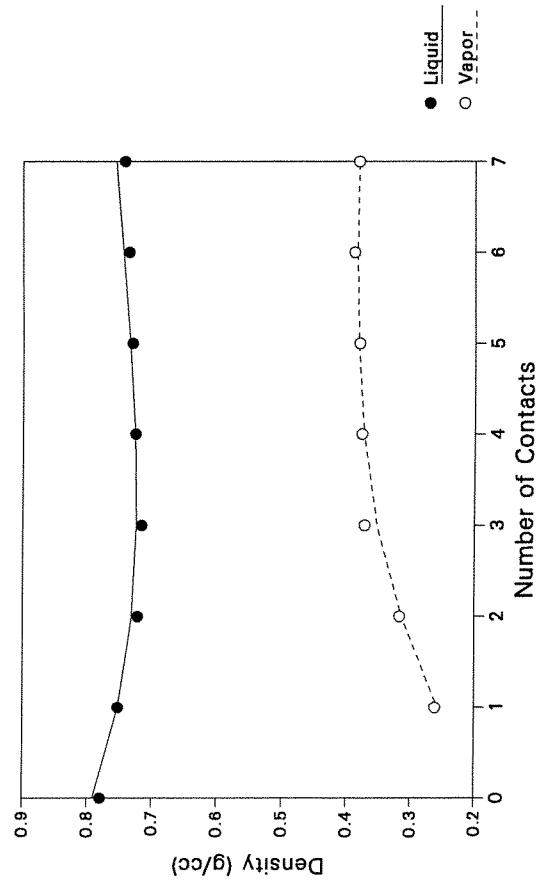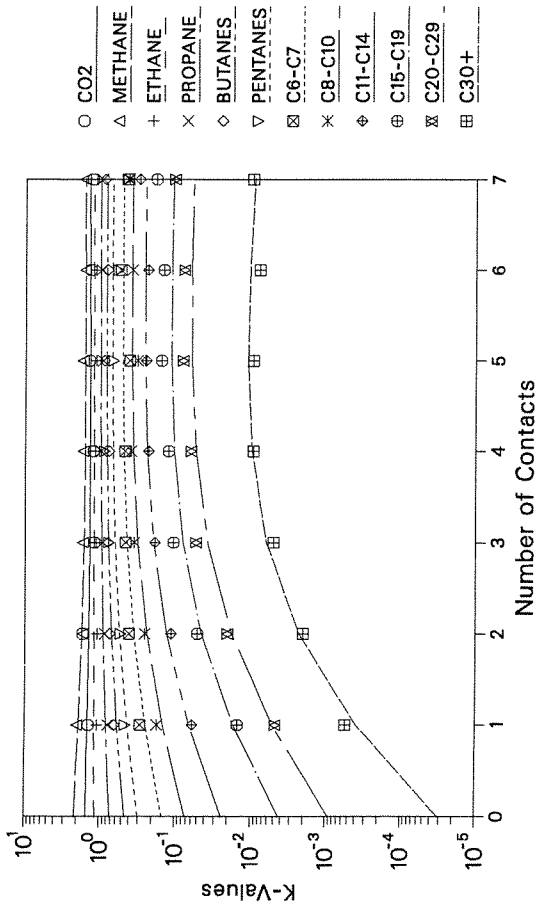

Fig. 1—Ternary diagram for a condensing-gas drive mechanism.

Fig. 2—Experimental slimtube recovery as a function of pressure with Solvent A.

O CO2
△ METHANE
+ ETHANE
✕ PROPANE
◇ BUTANES
▽ PENTANES
⊠ C6-C7
✳ C8-C10
⊕ C11-C14
⊞ C15-C19
⊠ C20-C29
⊞ C30+

Fig. 7—Experimental (symbols) and simulated (curves) K-values from multicontact experiment at 3,600 psig.
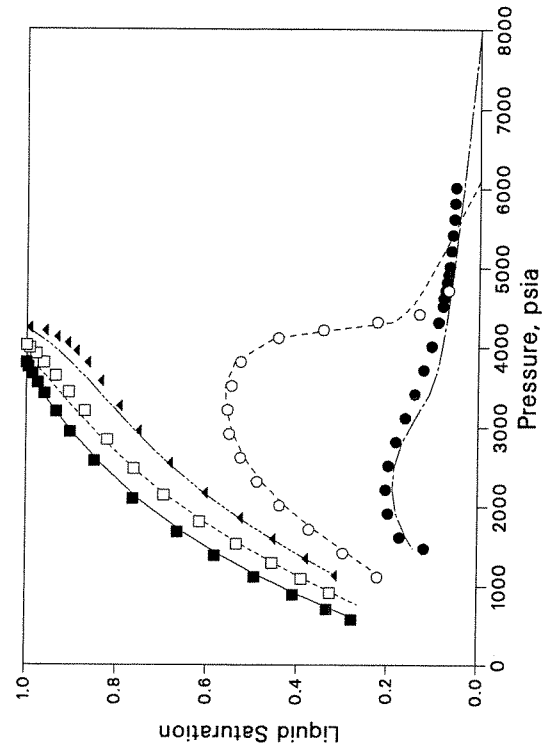

■ 0% Solvent
□ 25% Solvent
▲ 45% Solvent
○ 65% Solvent
● 85% Solvent

Fig. 8—Experimental (symbols) and simulated (curves) liquid saturation vs. pressure and percent solvent in solvent/oil mixture.
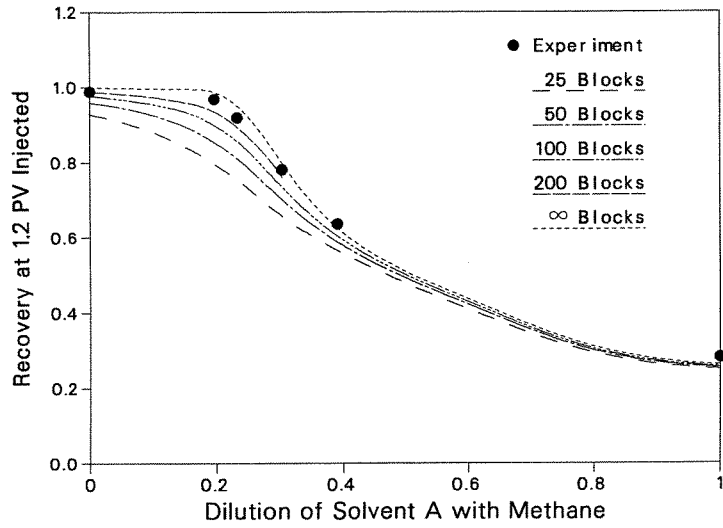

O CO2
△ METHANE
+ ETHANE
✕ PROPANE
◇ BUTANES
▽ PENTANES
⊠ C6-C7
✳ C8-C10
⊕ C11-C14
⊞ C15-C19
⊠ C20-C29
⊞ C30+

Fig. 5—Experimental (symbols) and simulated (curves) K-values from multicontact experiment at 3,100 psig.
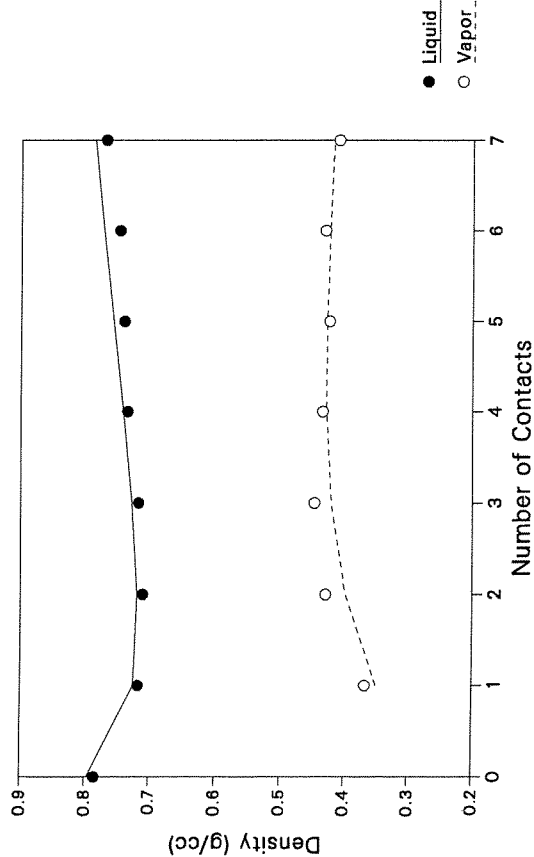
● Liquid
O Vapor

Fig. 6—Experimental (symbols) and simulated (curves) densities from multicontact experiment at 3,600 psig.

Fig. 9—Experimental, simulated, and extrapolated recoveries as functions of solvent dilution.
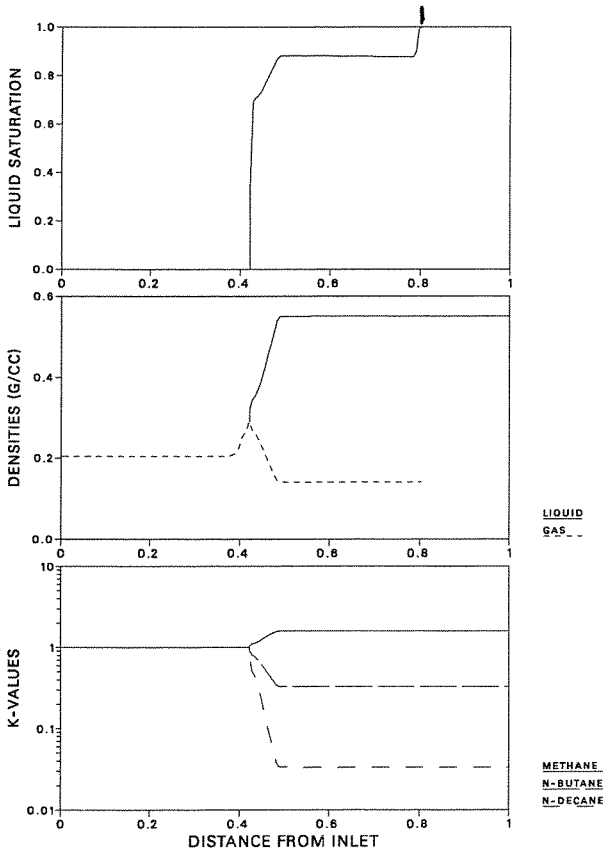

Fig. 10—Slimtube profile for a condensing-gas drive.
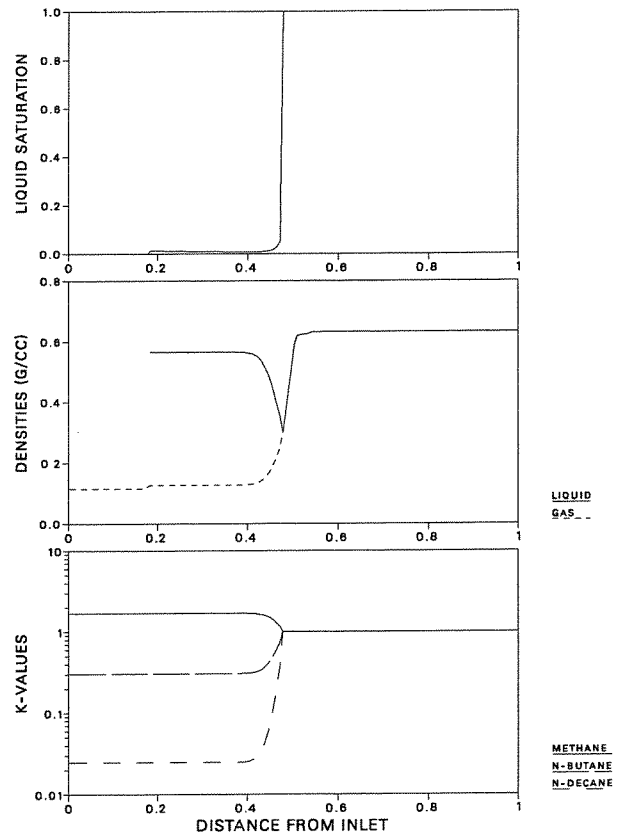

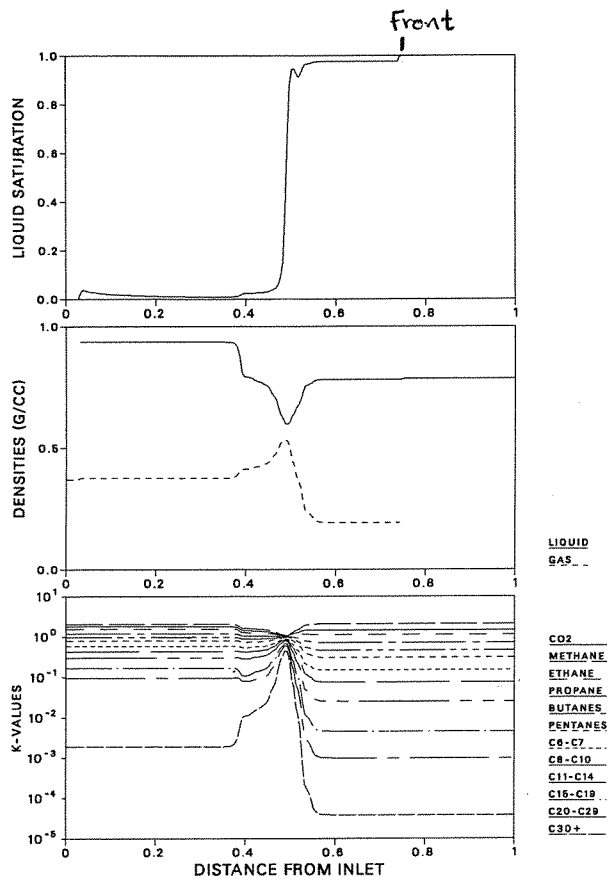Fig. 11—Slimtube profiles for a vaporizing-gas drive.

Fig. 12—Slimtube profiles for a condensing/vaporizing-gas drive (displacement of reservoir Fluid A by Solvent A).
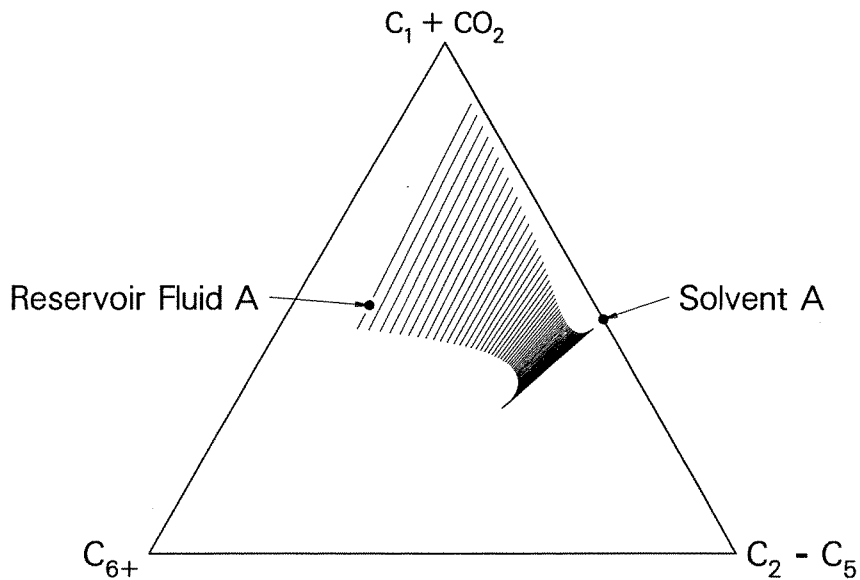

Fig. 13—Pseudoternary representation of a simulated multicontact experiment with reservoir Fluid A, 900 psi above apparent MMP.