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Quarterly Technical Progress Report

IMPROVED EFFICIENCY OF MISCIBLE CO_2 FLOODS AND ENHANCED PROSPECTS FOR CO_2 FLOODING HETEROGENEOUS RESERVOIRS

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OBJECTIVE

The objective of this experimental research is to improve the effectiveness of CO_2 flooding in heterogeneous reservoirs. Activities are being conducted in three closely related areas: 1) exploring further the applicability of selective mobility reduction (SMR) in the use of foam flooding, 2) exploring the possibility of higher economic viability of floods at slightly reduced CO_2 injection pressures, and 3) taking advantage of gravitational forces during low interfacial tension (IFT), CO_2 flooding in tight, vertically fractured reservoirs.

SUMMARY OF PROGRESS

Progress made this quarter in each of the three areas of the project is discussed below.

TASK 1 - CO_2-FOAMS FOR SELECTIVE MOBILITY REDUCTION (SMR)

Progress on this task in the past quarter has been made in the experimental study and modeling analysis of SMR-enhanced foam flooding. The experimental tests include mobility measurements of CO_2-brine mixture and CO_2-foam in a new series composite core. The numerical modeling examines the effect of flow geometry on the SMR-enhanced foam flooding in a simple field situation. In addition to this progress, three technical papers relevant to this task are being prepared for SPE conferences to be held this year in Midland and Tulsa.

Experiments

A second new series composite core was constructed by assembling two Berea core samples of differing permeabilies in the same coreholder. In this assembly, the unavoidable space between the two core faces was filled with a fine sand. The heterogeneity of this new system was determined by measuring the brine permeability at four sections along the core. Initial mobility experiments on two-phase flow of CO_2-brine show no pressure anomaly in the fine sand section. This finding suggests that a fine sand might be a better material to join cores than a fine filter paper when simulating longer flow systems.

Additional experiments were conducted on foam mobility measurements with this composite core. The results are presented in Fig. 1, where the mobility of CO_2-brine or CO_2-foam is plotted against the sectional permeability along the core sample. As shown on this graph, the slope of CO_2-brine mobility data of (as determined by the regression) is 1.46. A slope greater than one indicates that the mobility of the fluid is more than proportional to core permeability. As a consequence, the fluid will flow through higher permeability rocks at a higher rate than would be expected for the given pressure gradient. Such a feature is opposite to the nature of displacement of a SMR fluid and will result in a poor sweep efficiency in the oil recovery process. On the other hand, when 1000 ppm surfactant is added into the brine phase, the mobility of CO_2-foam is reduced and the slope falls to 0.51 for both surfactants: CD1050 and CD1045. A slope of 0.51 implies that the foam, as generated by these two surfactants, exhibits moderate SMR behavior. These results are similar to what we have previously reported, when SMR was observed in separate small core samples which are not in capillary contact. The small differences with earlier work could be the result of core size, core type, and brine concentration. We are currently conducting experiments to confirm these observations and we plan to use other types of surfactants with this same composite core system for further study.

Modeling

Numerical modeling work continues to examine the effect of radial flow geometry on oil recovery by using a SMR fluid in the displacement process. The results of this work show that CO_2-foam floods, augmented by SMR, show promise for improved oil recovery in which the recovery efficiency depends on the extent of SMR and the permeability contrasts that are normally encountered in the reservoir. The benefits of using SMR-enhanced foam in oil recovery become more obvious when the displacement of foam takes place in a radial flow geometry in the reservoir. As shown in Fig. 2, the breakthrough time of a moderate SMR-enhanced foam (exponent of 0.75) in a faster layer is delayed in a radial flow geometry when it is compared to that in a linear flow geometry. Furthermore, the pore volume of fluid required to achieve 90% of oil recovery can be reduced from 1.6 PV to 1.25 PV.

These results demonstrate the order of magnitude of the effect. In an actual reservoir with other considerations such as shape, well placement, horizontal as well as vertical permeability variations, and fluid properties, a much more detailed and sophisticated reservoir simulation must be used to assess the value of SMR-enhanced foam in the oil recovery application.

TASK 2 - REDUCTION OF THE AMOUNT OF CO_2 REQUIRED IN CO_2 FLOODING

During this quarter, good progress has been achieved in several areas. In the laboratory, achievements include the completion test of a conventional PVT study and CO_2 swelling tests for Sulimar Queen recombined live crude, recombination and a bubble point check for a large sample of Spraberry live crude, a number of compositional analyses of produced samples from a CO_2 gravity drainage test, and a series of mobility coreflood tests. Several programming bugs have been identified and eliminated in DOE's reservoir simulator MASTER, with some comparison runs with UTCOMP completed. Both are showing foam results similar to those obtained from earlier field tests. Two technical papers relevant to this task are being prepared for the 1996 SPE/DOE Symposium on Improved Oil Recovery to be held on April 21-24 in Tulsa.

PVT Studies

The laboratory work has been completed on a conventional PVT study on Sulimar Queen reservoir fluid and CO_2 was incrementally injected to 90 mole % CO_2. The PVT study was undertaken to obtain this information for another study and to establish a baseline for comparison when adding CO_2 to the system. The swelling tests can be used as a good, but conservative estimate, of the CO_2 MMP at reservoir temperatures below 120°F. This MMP estimate represents the upper pressure of the three phase region at high CO_2 concentrations in the pressure/composition phase diagram, as seen in Fig. 3. The temperature of this reservoir is in the 65 to 75°F range. The upper phase boundary of the three-phase region is less than 850 psig, which should be achievable in a 2000 ft deep reservoir. The swelling curve also provides information valuable for reservoir simulation on the amount of recovery to expect from reservoir crude due to oil swelling.

Spraberry

Bubble point tests have been completed on a sample of live Spraberry oil. This oil will be used for a number of tests during the next two quarters that will include MMP determinations, swelling tests, and continuous phase equilibrium tests. A series of compositional tests on samples of Spraberry crude produced from the gravity drainage tests, related to Task 3, were analyzed. The results of the analysis showed significant reduction in the C_{20+} components in the produced fluid in all samples except those taken at the end of the test when heat was applied to the system. The low C_{20}+ recovery is indicative of an extraction or stripping process by the CO_2 rather than displacement as the major production mechanism.

Coreflood Tests

Baseline experiments for coreflood foam tests were performed for various CO_2 flow fractions, 0.80, 0.67, 0.50, 0.33, and 0.20, by simultaneously injecting CO_2 and brine into a and brine-saturated core until a steady-state pressure drop across the core was obtained. Three flow rates, 16.8, 8.4, and 4.2 cc/hr were used during each CO_2 flow fraction test. The mobility of CO_2/brine for each test can be obtained based on the results from the tests of three different flow rates. The results indicate that the mobility of CO_2/brine increases with increasing CO_2 flow fraction. As hoped, the single phase mobility of brine and CO_2 are much higher than the mobility of CO_2/brine. The mobility data obtained from baseline experiments will be used to calculate the foam resistance factor of each test. Foam tests will be performed to examine the influence of foam quality at a lower range on CO_2-foam flow behavior.

Reservoir Simulations

Additional progress on the validation of foam options in MASTER was made in the past quarter. Both UTCOMP and MASTER use the same foam test to validate the foam options. However, the results of the foam test from MASTER are not similar to the results obtained from UTCOMP, indicating that bugs may still be in the code of MASTER. Currently, our time is spent debugging and validating MASTER. The effect of foam can be identified by comparing the results of the foam test with the results of the base case without foam.

TASK 3 - LOW IFT PROCESSES AND GAS INJECTION IN FRACTURED RESERVOIRS

Research continues in two primary areas: 1) Understanding the fundamentals of low interfacial tension behavior via theory and experiment and the influence on multiphase flow behavior and 2) Modeling low IFT gravity drainage for application of gas injection in fractured reservoirs.

In the first year of our contract, we presented all the fundamental background for reservoir IFT calculation of crude oil/gas mixtures. The calculation methodology developed was presented as a standard for industry's use in predicting IFT accurately. We presented evidence for the conditions in our first annual report showing that the scaling exponents can apply far from the critical point.

The first quarter of the second year was spent measuring the IFT of pure component liquid/vapor systems in our completed pendant drop apparatus. Our experimental data is presented in the quarterly report. The report supports the assumptions necessary for simple, yet theoretically accurate parachor calculations. The second quarter of year 2 was spent on CO_2 gravity drainage experiments. We presented experimental data and compared the results with a mathematical model of gravity drainage in the quarterly report.

While continuing measurement of IFT of multi-component systems, we devoted the third quarter of year 2 on CO_2/oil (non-equilibrium) gravity drainage experiments using a reservoir core at reservoir conditions.

We conducted a non-equilibrium gravity drainage experiment using a Spraberry core, stock tank oil and CO_2 at reservoir temperature near the MMP. A sketch of experimental apparatus was shown in the last quarterly report. In our experiment, a 4" x 24" reservoir core (0.01 md) taken from Spraberry Trend in West Texas was saturated with synthetic reservoir brine. The brine was displaced with STO to connate water saturation. During the gravity drainage process, CO_2 was injected into the annulus in the core holder and the temperature in the core holder was maintained at about 139°F. Pressure was between 2,000 psig and 1,500 psig, as seen in Fig. 4.

The oil recovery volume was collected at ambient pressure, seen in Fig. 5. The collected oil samples are mostly yellow and brown in color. Table 1 presents the composition difference between the input oil and the produced oil. Table 2 shows the density and viscosity of the produced oil at atmospheric pressure. Table 1 clearly shows that the produced oil is lighter than the input oil. More importantly, Table 1 indicates that some light hydrocarbons escaped with CO_2 gas during collection of the produced liquid. The hydrocarbon escape is because the liquid was collected at a temperature that is close to reservoir temperature. It is estimated that up to 70% of light hydrocarbons were lost during the experiment. Figure 6 presents corrected recovery volume using data from GC analysis. Figure 7 demonstrates the comparison between the experimental oil recovery and its matching with our mathematical model and procedure reported in the last quarterly report. Figure 8 shows calculated recovery components due to vertical drainage, horizontal diffusion and gas expansion caused by depressurization. It is indicated from Figure 8 that horizontal molecular diffusion is the dominating mechanism for the CO_2 oil recovery from the low permeability reservoirs. This is consistent with the composition and color of produced oil.

Table 1. Composition of separator oil and produced oil.

Hydrocarbon Number	STO	Mole Fraction Yellow Oil	Brown Oil
5	0.09114	0.00122	0.00143
6	0.06631	0.00058	0.00103
7	0.14649	0.00190	0.00612
8	0.10466	0.00585	0.01799
9	0.06115	0.01425	0.03063
10	0.05053	0.03841	0.05731
11	0.03736	0.06110	0.07372
12	0.03561	0.08715	0.09773
13	0.03313	0.10453	0.11466
14	0.02572	0.08705	0.09355
15	0.02151	0.07932	0.08366
16	0.02020	0.07220	0.07295
17	0.02088	0.07893	0.07774
18	0.01485	0.05368	0.05020
19	0.01609	0.05446	0.04840
20	0.01142	0.03545	0.03029
21	0.01068	0.03057	0.02560
22	0.01016	0.02579	0.02109
23	0.00957	0.02142	0.01730
24	0.00898	0.01721	0.01382
25	0.00599	0.01051	0.00853
26	0.00846	0.01187	0.00952
27	0.00574	0.00682	0.00551
28	0.00852	0.00867	0.00711
29	0.00583	0.00488	0.00406
30	0.00566	0.00414	0.00354
31	0.00569	0.00363	0.00320
32	0.00555	0.00320	0.00293
33	0.00536	0.00291	0.00280
34	0.00540	0.00283	0.00283
35	0.00550	0.00285	0.00296
36	0.00822	0.00439	0.00472
37+	0.12763	0.06224	0.00709
Total	1.00000	1.00000	1.00000
MW	219.39	251.80	222.34

Table 2. Density and viscosity of the yellow oil.

Temperature °C	Density g/cc	Viscosity cp
40	0.835	3.3
50	0.828	2.5
60	0.820	2.1
70	0.812	1.7

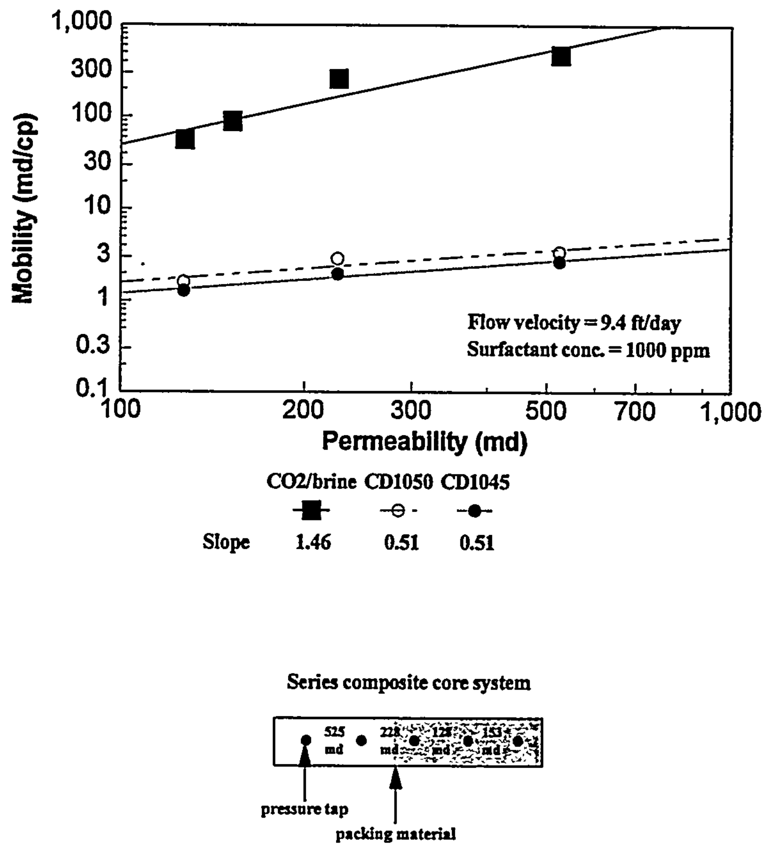

Fig. 1 Mobility dependence on permeability in a composite core.

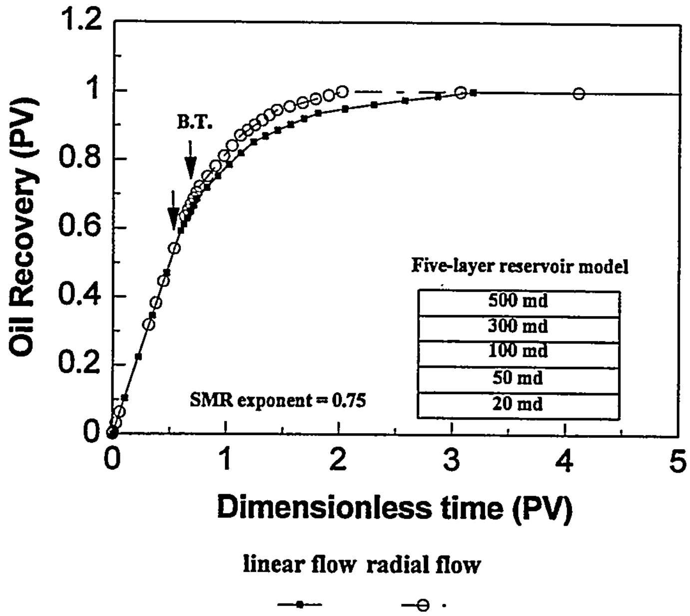

Fig. 2 Effect of flow geometry on oil recovery or vertical sweep efficiency in a five-layer reservoir model.

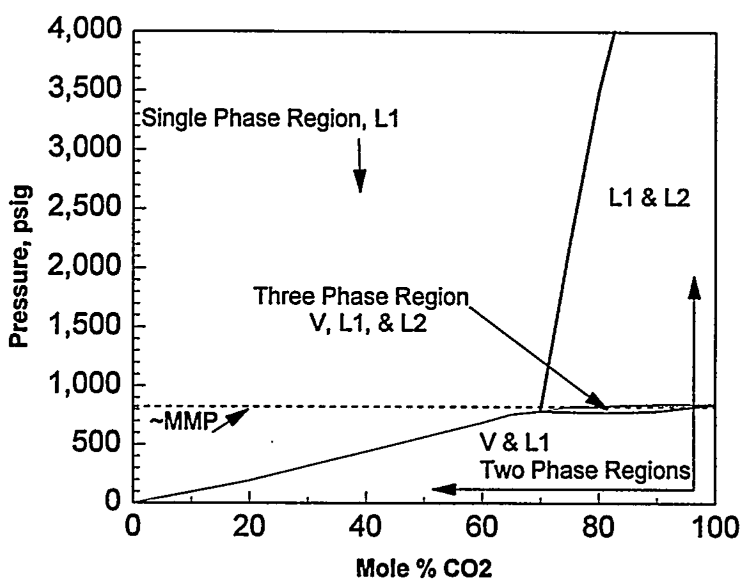

Fig. 3 Pressure-composition phase diagram for CO_2 added to Sulimar Queen Oil.

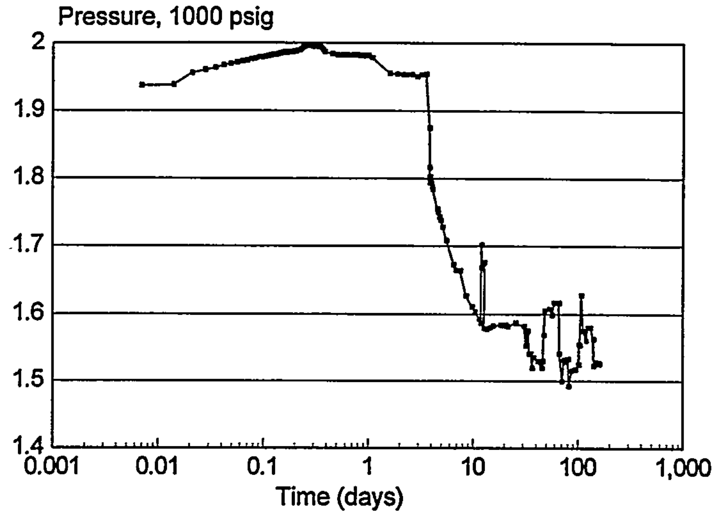

Fig. 4 Pressure schedule of experiment.

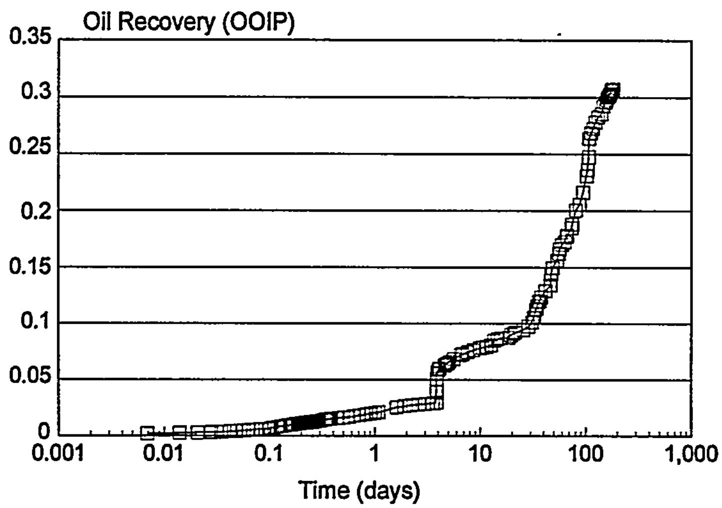

Fig. 5 Recovery from a Spraberry core.

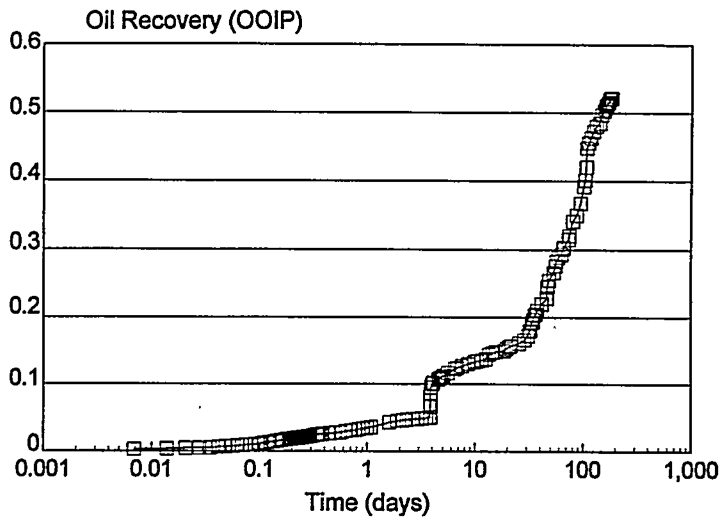

Fig. 6 Corrected oil recovery data.

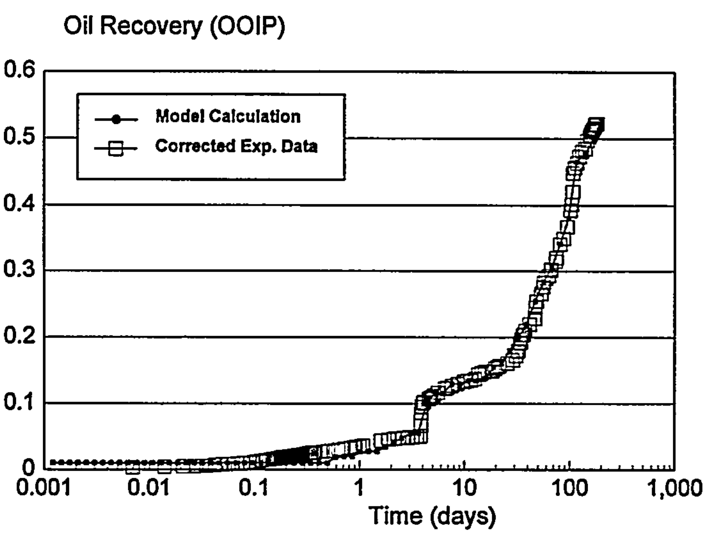

Fig. 7 History match of oil recovery.

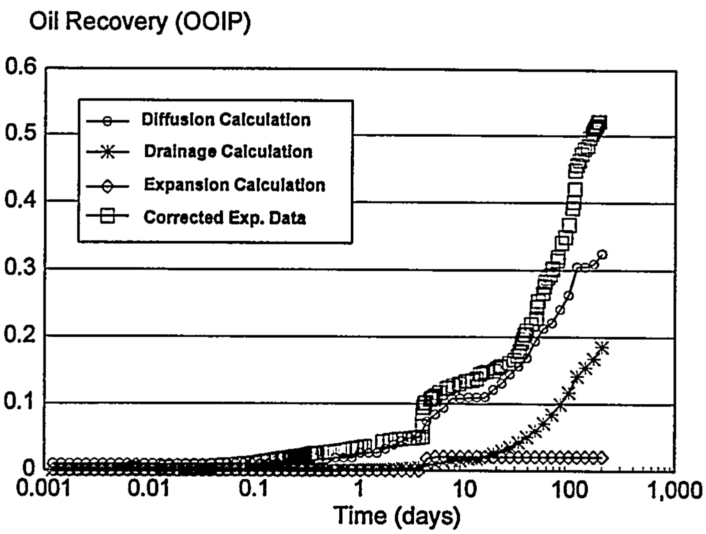

Fig. 8 Calculated recovery components.