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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

In this quarter PRRC researchers are beginning to observe positive results in the continuing laboratory work to determine the effect of capillary contact on SMR during flow of $CO_2$-foam in porous rock. Measurements of mobility in the coaxial regions of the cylindrical, two-permeability composite core have been obtained. Preliminary analysis has confirmed that the presence of surfactant in the brine phase flowing with the $CO_2$ decreases mobility by a greater fraction in the high permeability region than in the low. Consequently, investigators are initiating modest numerical model studies by which to evaluate the overall reservoir benefit from SMR in simple geometries. These models can quantify the gains to be made in production efficiency through the use of $CO_2$-foam with SMR.

Progress on this task in the past quarter has been made in the performance of laboratory experiments, in their analysis, and in computation of the reservoir situation in SMR-enhanced foam flooding. The experimental tests include mobility measurements in both series and parallel composite cores. The first embodiment of the experiments has made use of two Berea cores of permeabilities approximately 150 and 500 md, butted together end-to-end and separated by a thickness of one fine (5 micron) filter medium to fill the unavoidable irregularities between them. Data for calculation of mobilities are obtained from the two injection pump settings during combined flow at known rates of surfactant-brine and $CO_2$ through the composite core, and from pressure gradient measurements between adjacent pairs of the five taps spaced along it. For the parallel composite cores, measurement of the steady-state mobilities in the two permeability regions is accomplished in a complementary manner — in this case, the driving pressure gradient is the same for both, and the two flow rates must be measured separately.

Preliminary analysis of the results of these different experiments is given in the following paragraphs of this quarterly report. Additional analytical considerations are also described below for a new numerical modeling or simulation procedure designed to evaluate the reservoir benefits to be derived from foam floods with $CO_2$-foam floods that are augmented by SMR.

The most valuable results from laboratory foam experiments are obtained after saturations and pressure gradients have become steady, and the mobility has assumed a value that it can be expected to have in most parts of the reservoir. Despite this, it is also informative to examine the transitory situation in laboratory tests, during the saturation or flow rate changes in the beginning of an experiment. This is the case in both of the experiments mentioned in this report.

In the first experiment, two cores of different permeability have been placed in series in the same coreholder. Five pressure taps are mounted along the coreholder, defining four segments of the composite rock. The experiment yields records of four pressure differences, between each pair of successive pressure taps. Following the method used in earlier mobility tests with single cores and with cores in series in separate coreholders, the fluids are injected by two syringe pumps (a RUSKA for the $CO_2$, and an ISCO for distilled water forcing brine or surfactant-brine from a floating-piston cylinder). Pressure is maintained almost constant by leading the output fluids into a backwards-running ISCO pump, which takes in the output at the total rates of the other two. The four pressure drops are recorded as functions of time after change of the injected fluid, from brine alone to $CO_2$/brine or $CO_2$/brine-with-surfactant. During the time in which the saturation changes in different portions of the core, starting with the section nearest the inlet, the pressure transducers between the taps respond to those changes. As in traditional experiments, the progressive saturation change in this case can be viewed as the motion of a more or less diffuse boundary or front, across which the aqueous fluid saturation changes from high to low.

As displacement proceeds in this series experiment, the four pressure readings show moderate and smooth changes as the front advances along the composite core — with one exception. The pressure drop between taps number 3 and 4 exhibits a slightly different behavior, in that a sharp spike occurs at the beginning of the period during which the saturation change is expected to reach the third segment of the rock (that is, the first part of the second core). Our interpretation of this behavior is that the filter paper between the two cores acts initially as a barrier to the flow of the non-aqueous phase. The initial saturation of $CO_2$ in the filter medium and the effective permeability of $CO_2$ through it are both zero. Additional pressure is needed to force smaller bubbles of $CO_2$ through the filter paper. Apparently, pressure tap number 3 is closer to the inlet than is the filter paper between the two permeability cores, so that the enhanced transient pressure drop across the paper is included in the total seen by transducer 3.

In view of the fact that flow rates through the two parts of the series composite core are the same (after steady state is achieved), the steady-state mobilities of the rock segments are inversely proportional to the measured pressure drops between the corresponding taps. More complete and quantitative results will follow, as new composites where a different porous material is used to fill the space between the high and low permeability sections and as various surfactants are used.

In a parallel experiment to test the influence of capillary contact, it is interesting to observe the transient outflows, before steady saturations have been attained. The high and low permeability regions are both exposed to the same pressure drop, and the two flows are kept separate. To accomplish the separation, a special outflow endcap directs flow from the two regions into two separate TEMCO back pressure regulators (BPRs). The domes of each are loaded by the same Nitrogen pressure of 2100 psi, and a sensitive differential pressure transducer is used to monitor the small (<1.5 psi) pressure difference between the two regions of the endcap. At the beginning of each run, while the two coaxial regions are each saturated by aqueous fluid (either brine, or brine with surfactant), the ratio of flow rates from the central region and from the annulus are equal to the product of the permeability ratio and the area ratio. After the start of injection of $CO_2$ (and the reduction of the brine rate to meet the specification of 80% flowing quality) and as the experiment progresses, the separate fluid fronts in the two regions do not move forward at the same speed. This transient period is not observed by differences in pressure but by the differences in outflow rates of $CO_2$ and aqueous phase from the two regions. Changes in these rates take place both before and after breakthroughs of the $CO_2$ from the two regions, until establishment of a steady condition.

Even prior to the steady state, the effect of surfactant in the brine can be observed. Very early $CO_2$ breakthrough from the higher permeability sections of these composites is observed with $CO_2$/brine, as a result of the low viscosity of $CO_2$ and the high permeability contrast. The presence of surfactant in the brine causes the breakthrough times for both the high and low permeability zones to be more nearly equal. For instance, breakthrough of $CO_2$ from the higher permeability region is delayed by factors ranging from 1.2 to almost 5 units, depending on whether the smaller cross-section of the core (the annular-to central area ratio was about 8.0 units) contained higher or lower permeability sand, and on the type of surfactant and its concentration.

The ratio of steady-state mobilities in the cores were affected even more drastically. In the composite with high permeability in the center, the ratio between mobilities in the high and low permeability regions was reduced as much as from 40 to 6 units, and in the other composite core, the ratio was reduced by even a greater amount. These are of course preliminary results, not yet examining in detail the influence of type and concentration of surfactants. It is apparent, however, that SMR does occur when the high and low permeability rocks are in capillary contact. This result raises immediate questions concerning the way SMR can affect the economics of oil production, and how this type of $CO_2$-foam flooding can be most usefully applied.

Evaluating the effectiveness of an SMR displacing agent, researchers adopted the calculation techniques described by Lake for displacement through parallel layers of a formation and extended this method to consider the features of SMR (that is, of an analogous dependence of displacement fluid mobility on permeability) in standard modeling techniques. The reservoir model consists of an ensemble of one-dimensional elements arranged in parallel. This "layer-cake" reservoir is assumed to have no communication between layers in the vertical direction. The displacement of oil by the displacing fluid is assumed to be piston-like, and the dissipative effects of dispersion and diffusion are ignored. Furthermore, the mobility of the displacement fluid is assumed to be variable depending on the permeability, which indicates how different degrees of SMR will affect the result.

Based on these assumptions, several equations are derived to calculate the successive displacing front positions in each layer and subsequently to estimate oil recovery as a function of time and injected fluid volume.

Based on our preliminary calculations, we confirmed that the breakthrough time of the faster (higher permeability) layer is delayed, and the vertical sweep efficiency of the model is improved if the mobility of the injected fluid is reduced. This improvement is much more significant when an SMR fluid is used for the displacement. Even a slightly favorable SMR fluid, that shows a slight dependence of mobility on rock permeability, can significantly reduce the number of pore volumes required to achieve the same degree of recovery as that realized with an ordinary mobility reducing agent. Both the experimental and the numerical modeling work will continue. This project is demonstrating the existence of longer- as well as shorter-term benefits from the use of $CO_2$-foam. In addition to the immediate gains, such as were demonstrated in the East Vacuum oilfield in the earlier project "The Verification of $CO_2$-Foam", it is now becoming possible to quantify the longer-term increases in reserves and oil recovery that can be obtained by use of $CO_2$-foam.

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

The objective of Task 2 of the project is to demonstrate the feasibility of decreasing $CO_2$ requirements for $CO_2$ flooding. Two approaches are being used in this study: (1) decreasing the mass of $CO_2$ required to fill the reservoir and (2) increasing the injection gas sweep efficiency. The density of $CO_2$ is less at the minimum miscibility pressure than at several hundred psi higher where most systems are being flooded; this density decrease can be more than 50 percent. A concern is whether the decreased density will also be accompanied with a decrease in sweep efficiency. Thus, methods that can increase sweep efficiency are being tested that will prevent the reduction in sweep efficiency or perhaps increase it. Methods for improving sweep efficiency are using foaming agents in the brine that is injected alternating with the gas (WAG) and using horizontal injection wells.

The coding has been completed for a horizontal model and two foam options; all three have been added to MASTER (DOE's pseudo miscible reservoir simulator) and one foam option has been added to UTCOMP (UT Austin's compositional reservoir simulator). Validation tests have continued for each option that has been added to MASTER and UTCOMP. Figure 1 shows the oil rate and water/oil ratio (WOR), predicted by MASTER using the problem from the "Seventh SPE Comparative Solution Project: Modeling of Horizontal Wells in Reservoir Simulation," SPE paper 21221. The two dotted lines in each plot denote the upper and lower boundaries of the results of studies from 14 organizations, as presented in the paper.

The paper, "Characterization and Multiphase Equilibrium Prediction of Crude Oil Heavy Components," presented at the Spring AIChE meeting, has been reviewed and accepted for publication early next year in *Fuel Science & Technology International.*

Earlier tests at the PRRC demonstrated the durability of high quality foam using the foaming agent, Chevron Chaser CD1045®. However, the quality of foam during a foam flooding is not limited to the higher range. Thus, foam tests are in progress to help determine the conditions to generate foam in the lower range of foam quality. In addition, the effects of pressure on foam flooding and oil recovery will be examined.

## 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 calculation of reservoir IFT of crude oil/gas mixtures. The calculation methodology developed was presented as a standard for industry use in predicting IFT accurately. Our methodology was based on certain assumptions concerning universal scaling laws. The assumptions have theoretical justification, yet no proof has been established in the literature concerning the applicability of critical scaling exponents at conditions far from the critical point.

The first quarter of year 2 was spent measuring the IFT of pure component liquid/vapor systems (water, decane, and $CO_2$) in our completed pendant drop apparatus.

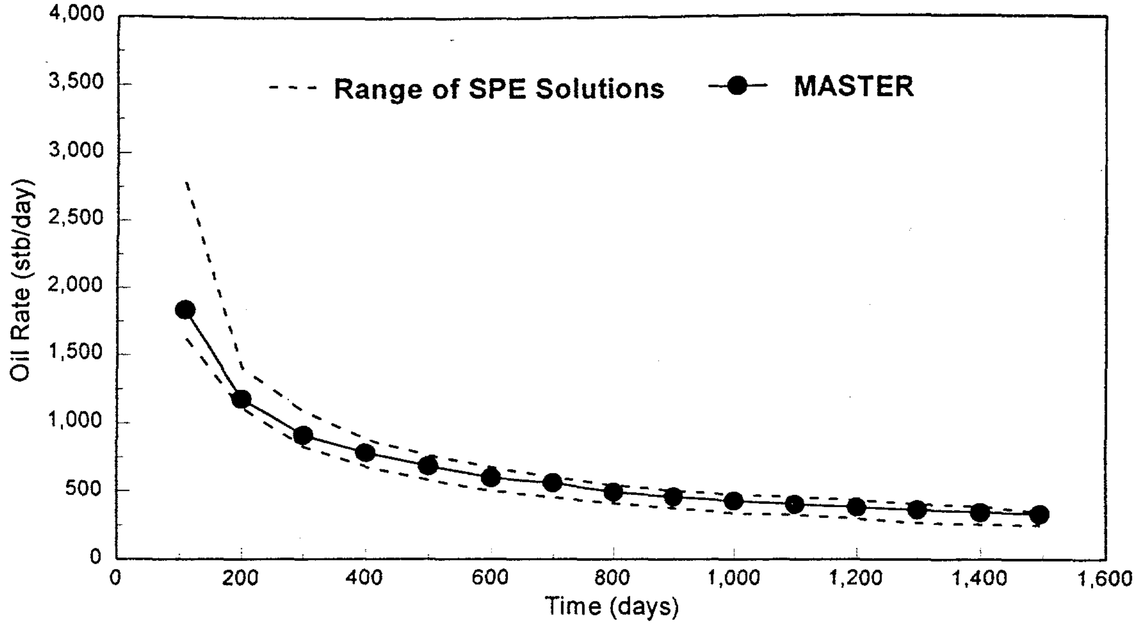
### Status of Pendant Drop Apparatus

The system is fully operational. We are able to circulate fluids and form drops through a variety of needle bore sizes. Densities of equilibrated phases can be measured by circulating through the densitometer. Thus, we are able to measure IFT and density differences between the liquid and vapor at a variety of temperatures and pressures representative of reservoir conditions. The remaining two years of this contract will be devoted to fundamental issues concerning prediction of IFT during gas injection processes.

### Experiments

Our pendant drop apparatus for IFT measurements consists of the pendant-drop forming system, density detection system, video imaging system, and image processing hardware and software. Using this apparatus, we have successfully measured the IFTs of water and decane under room pressure and temperatures. The results are consistent with data appearing in the literature. We have also measured the IFT of pure $CO_2$ in the near critical region. Experimental pressure and temperature to date have reached near critical point of the $CO_2$ (1071 psia, 88°). Figure 2 illustrates the measured densities of $CO_2$ liquid and vapor. The minimum density difference is 0.49 g/cc at reduced temperature ($1 - T/T_c$) of 0.027. Figure 3 shows a plot of the density difference versus the reduced temperature. The slope of the best fitted line to the data is estimated to be 0.380, while its theoretical value is 0.325 in the critical region. Figure 4 demonstrates the relation between the measured IFT and reduced temperature. Figure 5 presents the relationship between the measured IFT and density difference. The data form a line with an estimated slope of 3.938, while its theoretical value is 3.88 in the critical region. The lowest IFT value to date is 0.52 mN/m at pressure of 846 psig and 72°F. This value indicates that we are in the neighborhood of the critical point of $CO_2$.

# Verification of Horizontal Feature in MASTER



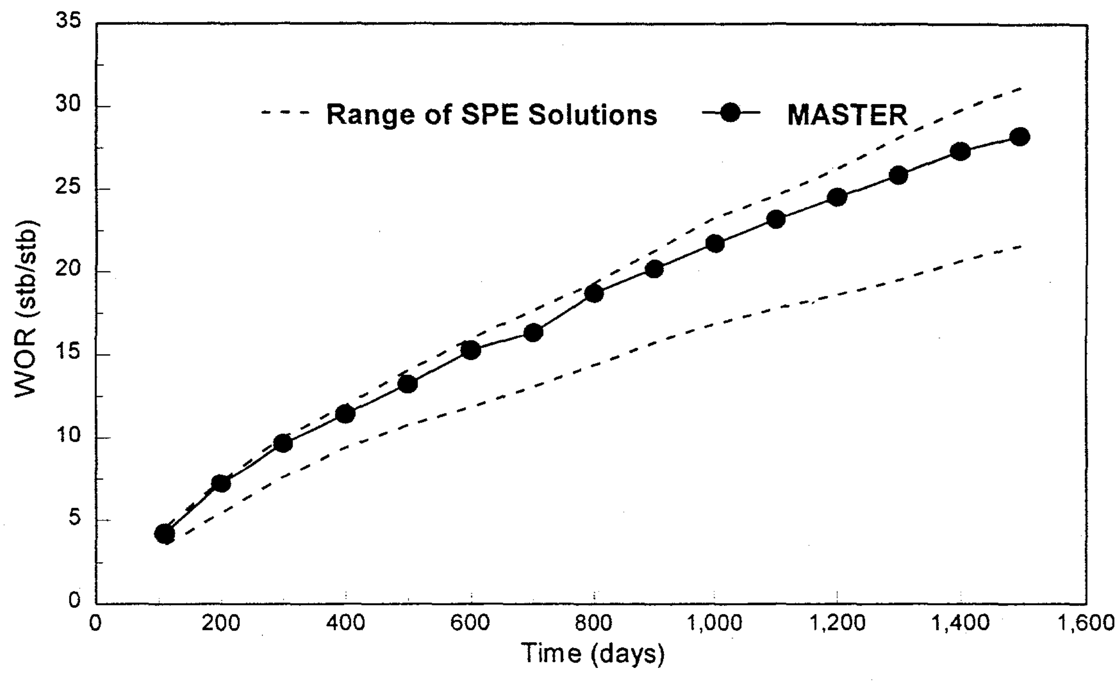




Fig. 1. Comparison of oil rate and water-oil ratio for Case 3a of the seventh SPE Comparative Solution Project.

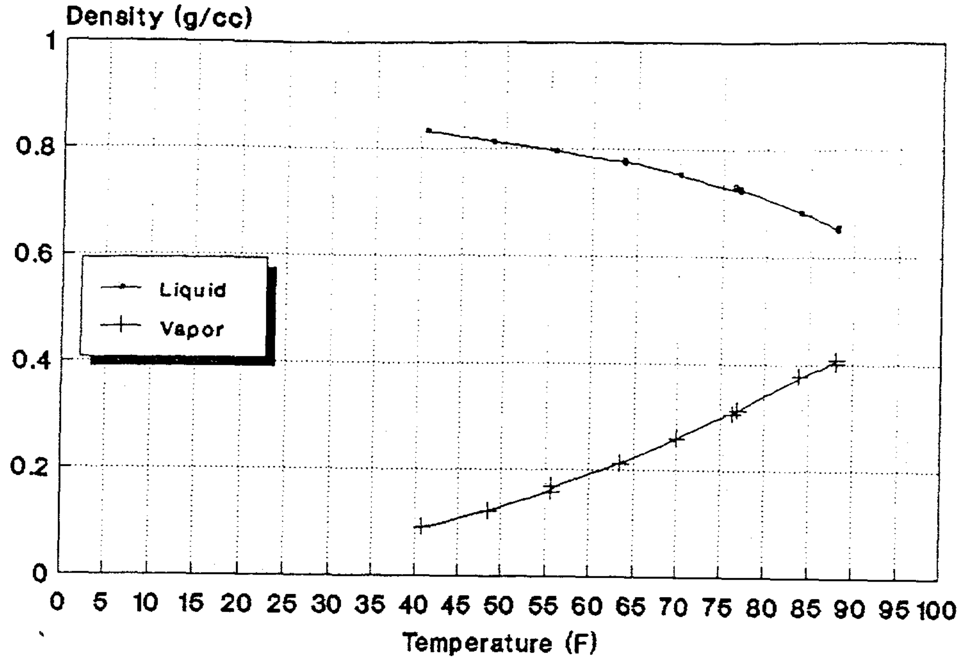



Fig. 2. Densities of $CO_2$ liquid and vapor.

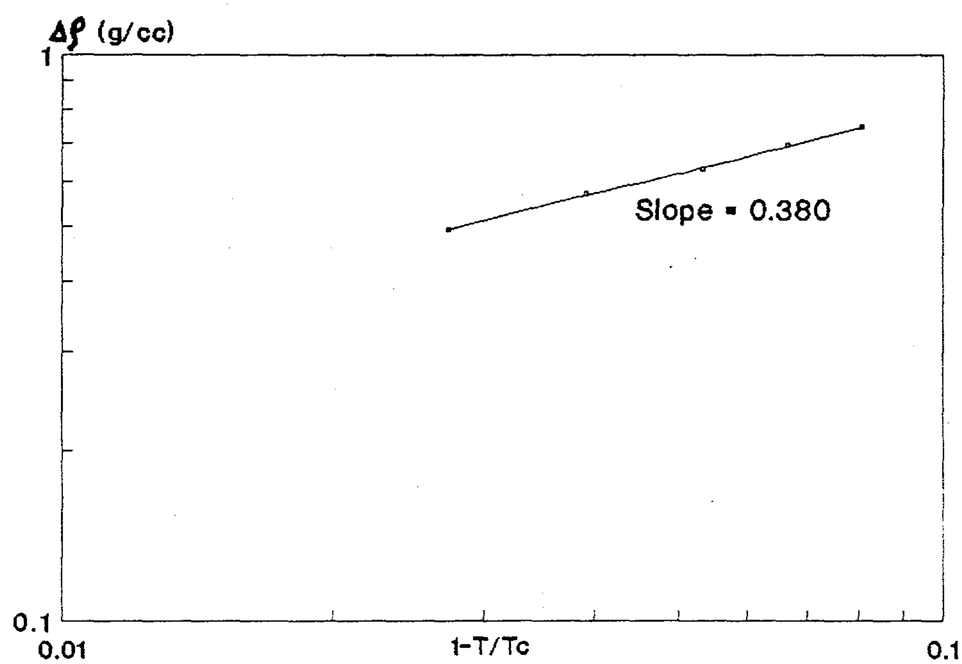



Fig. 3. Density difference vs reduced temperature for $CO_2$.

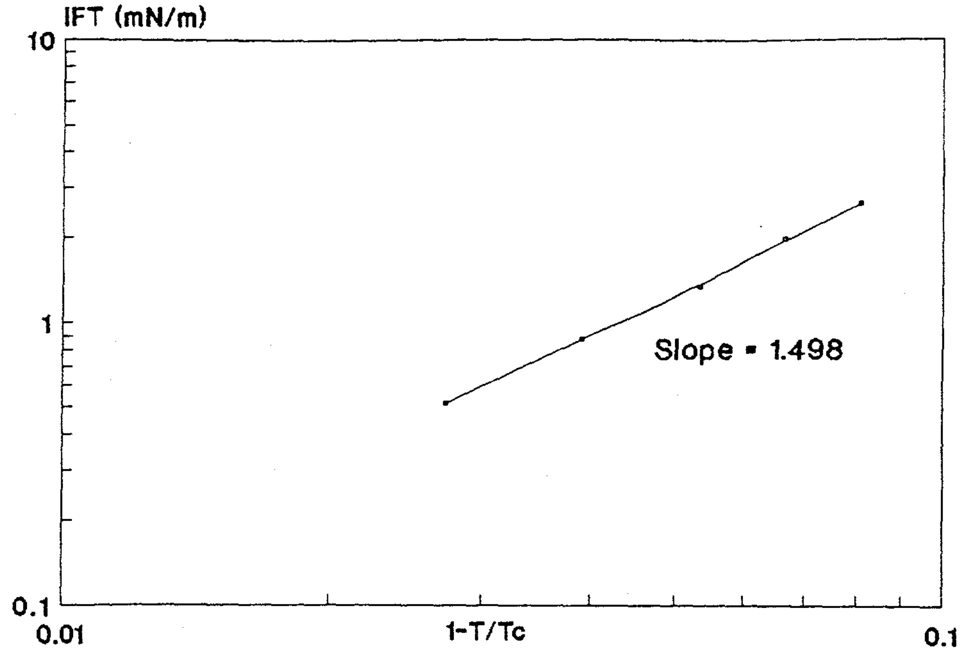



Fig. 4. Interfacial tension vs reduced temperature for CO2.

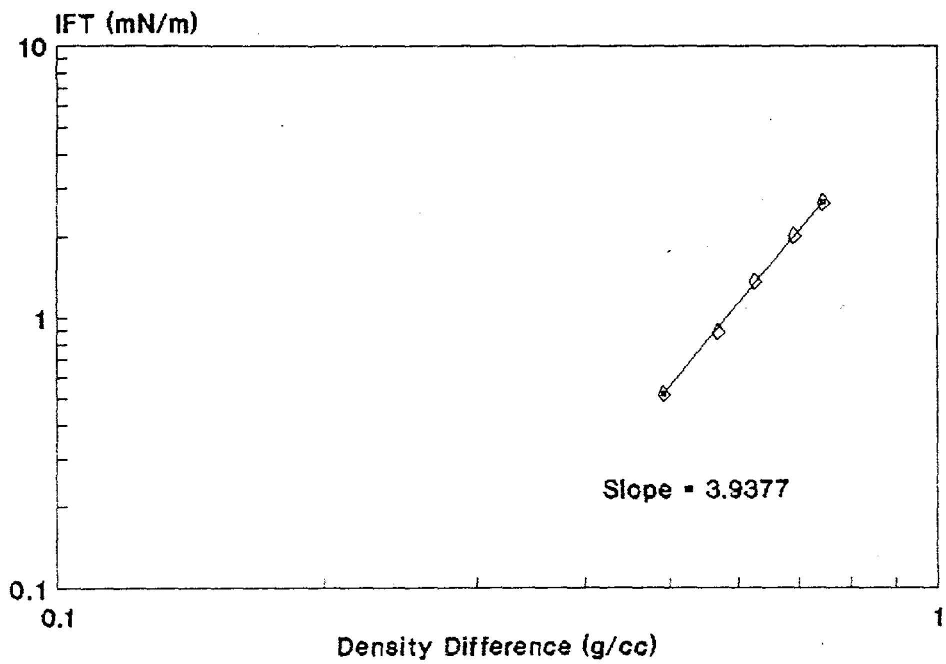



Fig. 5. Interfacial tension vs density difference for $CO_2$.