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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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US/DOE Patent Clearance is not required prior to publication of this document.

Quarterly Report 1996 (January 1 - March 31, 1996)

Objective

The objective of this research project is to improve the effectiveness of CO_2 flooding in heterogeneous reservoirs. Research is 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 reduced CO_2 injection pressures, and 3) understanding low interfacial tension (IFT) mechanisms with application to CO_2 flooding in tight vertically fractured reservoirs.

Summary of Progress

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

Task 1 - CO_2-Foams for Selective Mobility Reduction (SMR)

During the study of CO_2-foam a number of systems have been found where mobility reduction is not simply proportional to rock permeability. This abnormal behavior is referred to as Selective Mobility Reduction (SMR). We are looking for and developing the understanding of systems were SMR favors more uniform sweep by promoting the same flow velocity in both high and low permeability regions of the rock. This effect will be used to enhance the mobility control associated with CO_2-foam systems in reservoirs. During the past quarter, two new surfactants (CD1040 and Dowfax 8390) were tested. Both reduced mobility, but CD1040 exhibited stronger SMR than DOWfax 8390.

Accomplishments

Additional experiments were conducted on foam mobility measurements with the same composite core as described previously[1]. Two different surfactants, Chaser CD1040 and Dowfax 8390, were used to generate dense CO_2 foam. 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. Since the same porous media is used for all experiments, mobility data for CO_2-brine are repeated here for reference. As described in Darcy's Law, the slope of the line (mobility versus permeability, see Fig. 1) determined from the regression is used as an indicator to exhibit how favorable the mobility dependence of fluid is to permeability. A slope of less than one shows favorable dependence or SMR which leads to a more uniform displacement front when the foam is flowing through a heterogeneous porous media. When 1000 ppm of surfactant is added to the brine, the foam exhibits different degrees of SMR behavior and mobility reduction depending on the type of surfactant. For example, the mobility reduction is less with Dowfax 8390 as a foaming agent compared to Chaser CD1040. Also, CD1040 shows more favorable SMR (slope of 0.78) compared to Dowfax 8390 (slope of 0.98). Both foams, nevertheless, show better mobility dependence on the rock permeability as opposed to the mixture of CO_2/brine flowing through the composite core sample.

Future Work

Up to now, SMR behavior has been observed to be surfactant-type dependent. It is apparent that some of the surfactant properties could contribute to this special feature of foam. In order to re-examine the surfactant properties and foam properties at reservoir conditions, we are revamping our foam durability measurement apparatus during the upcoming quarter. We plan to conduct experiments to measure the interfacial tension (IFT) between surfactant and dense CO_2. These experiments are needed to determine critical micelle concentration (CMC) of each surfactant, to compare stability of foam among different surfactants, and to correlate these properties with SMR behavior reported in our experiments.

Task 2 - Reduction of the Amount of CO_2 Required in CO_2 Flooding

The major front end expense of CO_2 floods is the purchase of CO_2. This task examines methods of reducing the CO_2 required per barrel of improved oil recovery. Two methods to accomplish this task are being examined: 1) reduction of the mass of CO_2 required by increasing the fill volume per CO_2 mass by reducing the flood pressure and 2) improving sweep efficiency principally using CO_2-foam.

We have continued work in the areas of phase behavior, core flooding, and developing improved reservoir models. We have completed several fluid studies required to understand the pressure effect on CO_2-reservoir fluid phase behavior. Our coreflood studies examined the effect of flow rate, surfactant concentration, foam quality, and rock properties on the resistance factor. Finally, we have continued developing foam models and testing them in reservoir simulators.

Accomplishements

Phase Behavior Studies

CO_2-reservoir phase behavior tests in a static cell have been completed on recombined Spraberry reservoir oil. This information will be used to predict miscibility development, tuning equation of state models, and understanding the role of interfacial tension on MMP.

Three slim tube tests were completed at different flow rates and pressures by injecting CO_2 into Spraberry oil that had been weathered at 138°F. At 2100 psig this system is still immiscible and does not appear to be near miscibility. In contrast, Spraberry separator oil developed multi contact miscibility at about 1600 psig. The loss of significant amounts of intermediate hydrocarbons (C5 through C10) raised the minimum miscibility pressure as much as 1000 psi.

Coreflood Tests

Coreflood foam tests were performed at various CO_2 fractions (0.2, 0.333, 0.5, 0.667, and 0.8) by simultaneously injecting CO_2 and surfactant solution into a surfactant solution saturated core until a steady-state pressure drop across the core was obtained. The surfactant concentration was 2500 ppm. The testing flow rate was 4.2 cc/hr. The pressure drop across the core for the foam tests was significantly higher at each CO_2 fraction than that of the baseline experiment completed previously(1). The results indicate that the pressure drop for the foam tests increased with increasing CO_2 fraction. However, when the CO_2 fraction was decreased to a previously measured lower value, the pressure drop was greater than the original test indicating hysteresis. In addition, the permeability of the core could not be restored to the original value before the foam tests. Hysteresis might be due to the effect of surfactant adsoprtion, such that the core permeability was permanently altered. Even though the core could not be restored to the original permeability, the CO_2-surfactant solution mobilities were always higher than the baseline tests. Currently, another new core is being tested. This new core was prepared by using a different firing method and should eliminate the hysteresis that was observed in the previous core.

Reservoir Simulations

Both MASTER and UTCOMP simulators have been successfully modified to simulate foam flooding processes where the resistance factor data are input in database format. In the validation exercises, an injection schedule that mimics an actual foam field pilot test was used. The simulation results show an increase in the oil production rate, attributed to the effects of foam, and are consistent with the observation from the foam field pilot. The results also show successful profile modification because of the presence of foam, thus resulting in significant sweep improvement. Agreement between MASTER and UTCOMP was good. Some of the modeling results are being presented at the SPE/DOE Tenth Symposium on Improved Oil Recovery.

Future Work

During the next quarter we will complete a series of dynamic phase behavior tests that are required to understand and predict the dynamic phase behavior changes in the reservoir during CO_2 injection. This information combined with slim tube test and IFT information will provide a comprehensive overview of what is occurring on a microscopic level in fluid interaction in the reservoir. Development of a reservoir description that can be used in the simulation of a CO_2-foam pilot will be started during the next quarter with the completion of the simulation during the following quarter.

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 the current 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's use in predicting IFT accurately. We presented evidence for the conditions(2) showing that the scaling exponents can apply far from the critical point. This evidence greatly facilitates calculation of accurate IFT.

Many experiments were conducted to support the methodology by measuring the IFT of pure component liquid/vapor systems with a reservoir condition pendant drop apparatus. The experimental data presented(1) supports the assumptions necessary for simple, yet theoretically accurate parachor calculations. During the course of low IFT studies, we have focused on CO_2 gravity drainage in Berea and reservoir whole core. Such experiments have direct application to improving oil recovery from naturally fractured reservoirs by gas injection.

Accomplishments

In addition to the CO_2 IFT measurements reported[1,2,3], we have conducted more measurements in the low IFT region for pure CO_2. Fig. 2 demonstrates results from our second dataset. Fig. 2 indicates that in low IFT region, the IFT values extracted from pendant drop profiles using the conventional shape factor method are greater than expected on the basis of theoretical analysis of critical scaling. We measured IFT of liquid/liquid systems consisting of brine (2% CaCl) heptane and isopropanol. The result, as shown in Fig. 3, demonstrates the same trend seen in Fig. 2. We then conducted a more accurate experiment for CO_2 IFT by minimizing change in experimental conditions between test points. The result is plotted in Fig. 4. Again, it shows deviation of calculated IFT values from the theoretical trend.

As the IFT decreases below about 1 mN/m, pendant drops tend to elongate due to the increased prominence of gravity. The drop is very small at low IFT and neck curvature is less pronounced. In this case, the shape factor method is difficult to apply because the diameter (Ds) of the drop at the elevation of the equatorial diameter (De) from the apex is strongly affected by the presence of the needle tip. Also, wetting behavior of the tip or so called "climbing" effect deforms the shape of the pendant drop. It is reasonable to believe that low IFT determined based on drop edge above the equator (such as the shape factor method) is erroneous in such a case.

To avoid the effect of the needle tip on low IFT measurements, we developed a new method for the determination of IFT from pendant drops. The new method is fomulated on the basis of equilibrium forces acting upon the lower half of the pendant drop. The hemispherical portion of the pendant drop edge below the equator is used for IFT determination. The result of IFT determined using this new method was compared with other methods found in the literature for water, normal decane, decyl alcohol, 2,3,4 trimethyl pentane, normal heptane, hexadecane and toluene under ambient conditions. This comparison shows very good consistency among the methods in the high IFT region (IFT > 10 mN/M). Using our pendant drop generating apparatus and image processing system, we tested the new method under various conditions for water, normal decane, ethane and CO_2. Fig. 5 show comparisons of IFT determined using the new method and the shape factor method. The new method appears to be more accurate than the shape factor method based upon critical scaling arguments. It is believed that the new method is more useful for ultra-low IFT determination because it allows calculations of IFT from very small droplets as long as the droplets have equators developed.

Future Work

Whole core gravity drainage experiments continue and more are planned for upcoming quarters. We are also focused on measuring IFT of crude oil/CO_2 systems and relating those measurements to the MMP and capillary number, in coordination with Task 2

Task 4 - Technology Transfer

For this project to have influence on practices in the oil industry and thus to be productive, knowledge about our research must be widely publicized. During the past quarter, six SPE papers were written, two of which have been presented orally[4,5] and the other four will be presented during the next quarter.[6-9]

References

1. F. David Martin, Reid B. Grigg, and David S. Schechter, Improved Efficiency of Miscible CO_2 Floods and Enhanced Prospects for CO_2 Flooding Heterogeneous Reservoirs, DOE Contract No. DE-FG22-94BC14977, *Quarterly Report,* October 1-December 31, 1995.
2. Reid B. Grigg, John Heller, and David S. Schechter, Improved Efficiency of Miscible CO_2 Floods and Enhanced Prospects for CO_2 Flooding Heterogeneous Reservoirs, DOE Contract No. DE-FG22-94BC14977, *Annual Report,* 1995.
3. David S. Schechter and B. Guo, *Parachors Based on Modern Physics and Their Uses in IFT Prediction of Reservoir Fluids,* paper SPE 30785 prepared for presentation at the SPE Annual Technical Conference & Exhibition, Dallas, TX, October 22-25, 1995.
4. J.S. Tsau and J.P. Heller, *How Can Selective Mobility Reduction of CO_2-Foam Assist in Reservoir Floods?,* paper SPE 35158 prepared for presentation at the Permian Basin Oil & Gas Recovery Conference, Midland, TX, March 27-29, 1996.
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6. D.S. Schechter and B. Guo, *Mathematical Modeling of Gravity Drainage After Gas Injection Into Fractured Reservoirs,* paper SPE/DOE 31570 prepared for presentation at the SPE/DOE Tenth Symposium on Improved Oil Recovery, Tulsa, OK, April 21-24, 1996.
7. S.H. Chang and R.B. Grigg, *Foam Displacement Modeling in CO_2-Flooding Processes,* paper SPE/DOE 35401 prepared for presentation at the SPE/DOE Tenth Symposium on Improved Oil Recovery, Tulsa, OK, April 21-24, 1996.
8. H. Yaghoobi, J. Tsau, and J.P. Heller, *Improving CO_2 Floods in Heterogeneous Media,* paper SPE/DOE 35403 prepared for presentation at the SPE/DOE Tenth Symposium on Improved Oil Recovery, Tulsa, OK, April 21-24, 1996.
9. R.B. Grigg, M.D. Gregory and J.D. Purkaple, *The Effect of Pressure on Improved Oilflood Recovery From Tertiary Gas Injection,* paper SPE/DOE 35426 prepared for presentation at the SPE/DOE Tenth Symposium on Improved Oil Recovery, Tulsa, OK, April 21-24, 1996.

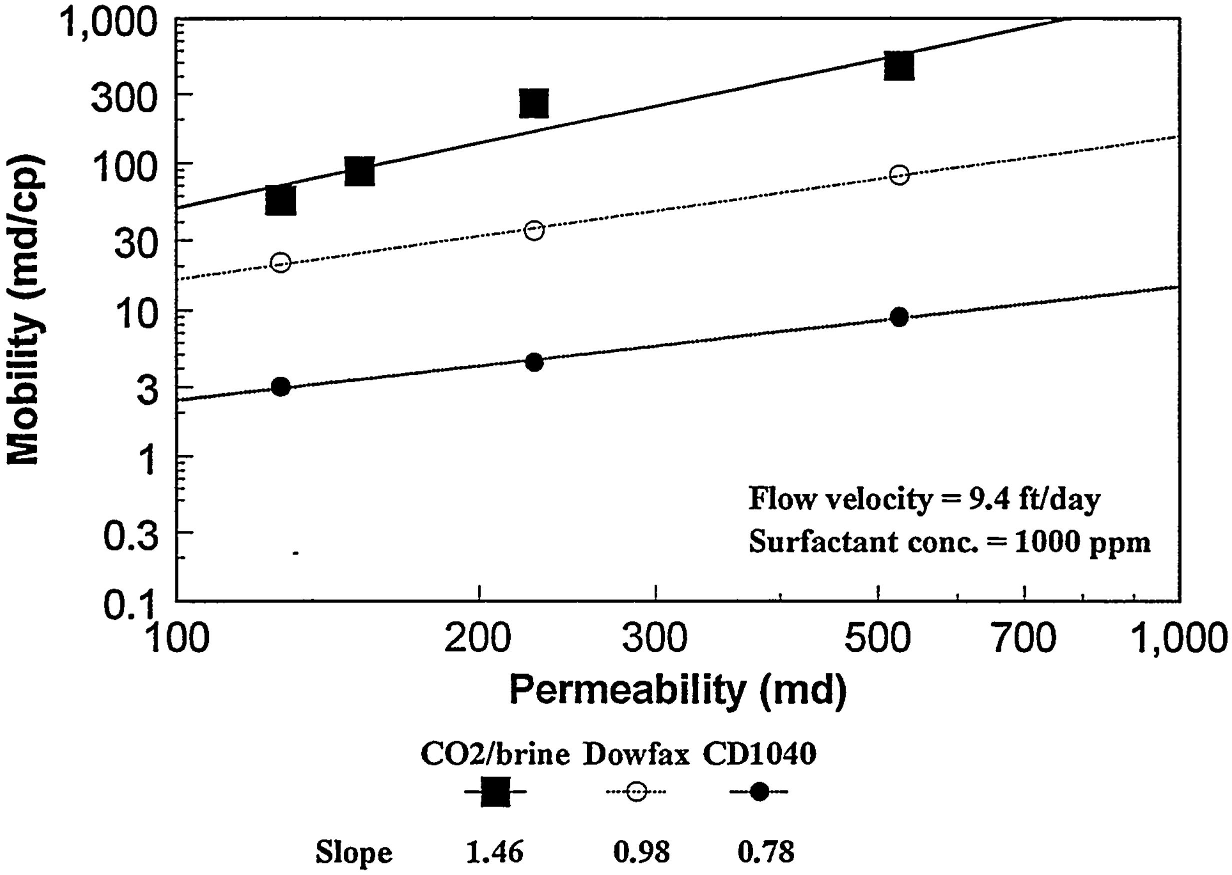

Figure 1. Mobility dependence on permeability in a composite core.

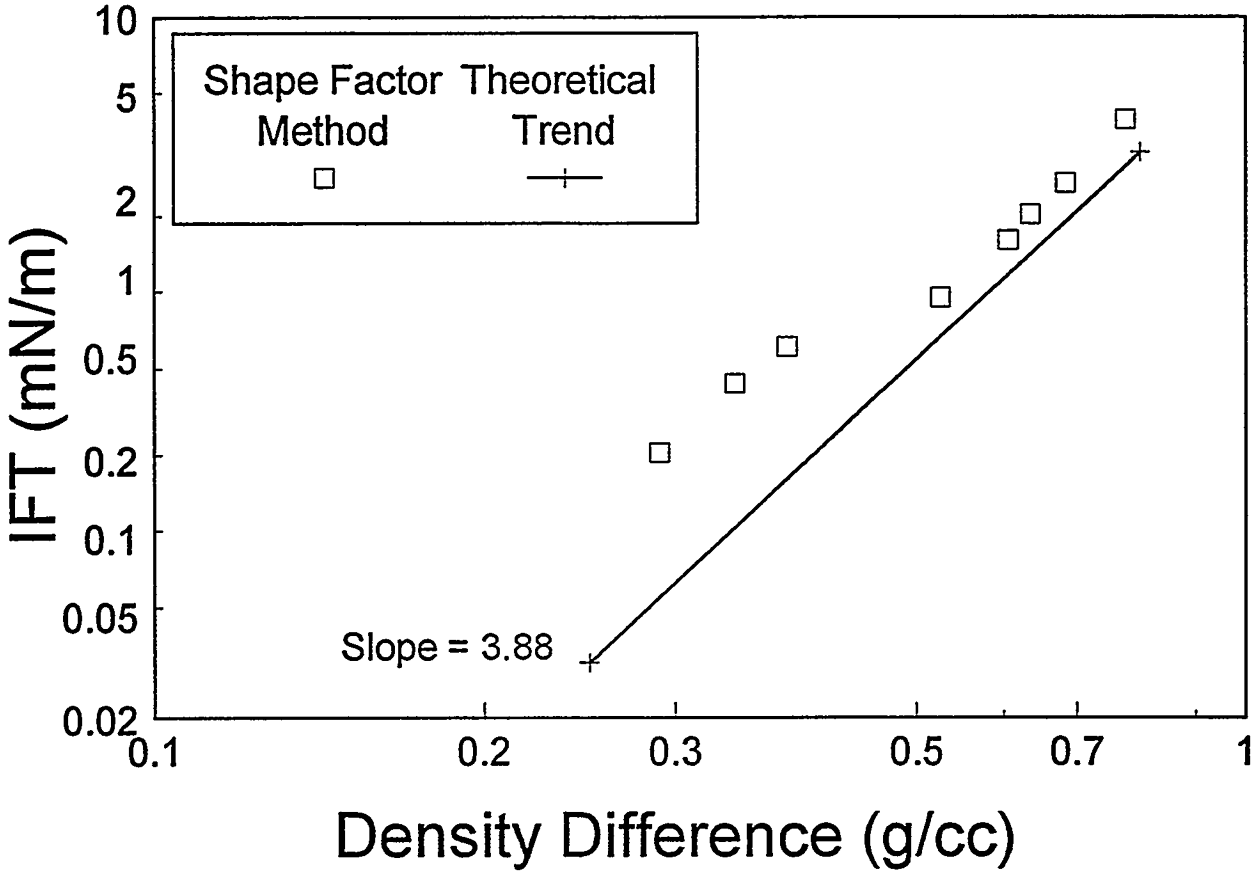

Figure 2. IFT vs. density difference for CO_2. Pendant drops created along CO_2 saturation curve and IFT calculated by conventional shape factor method.

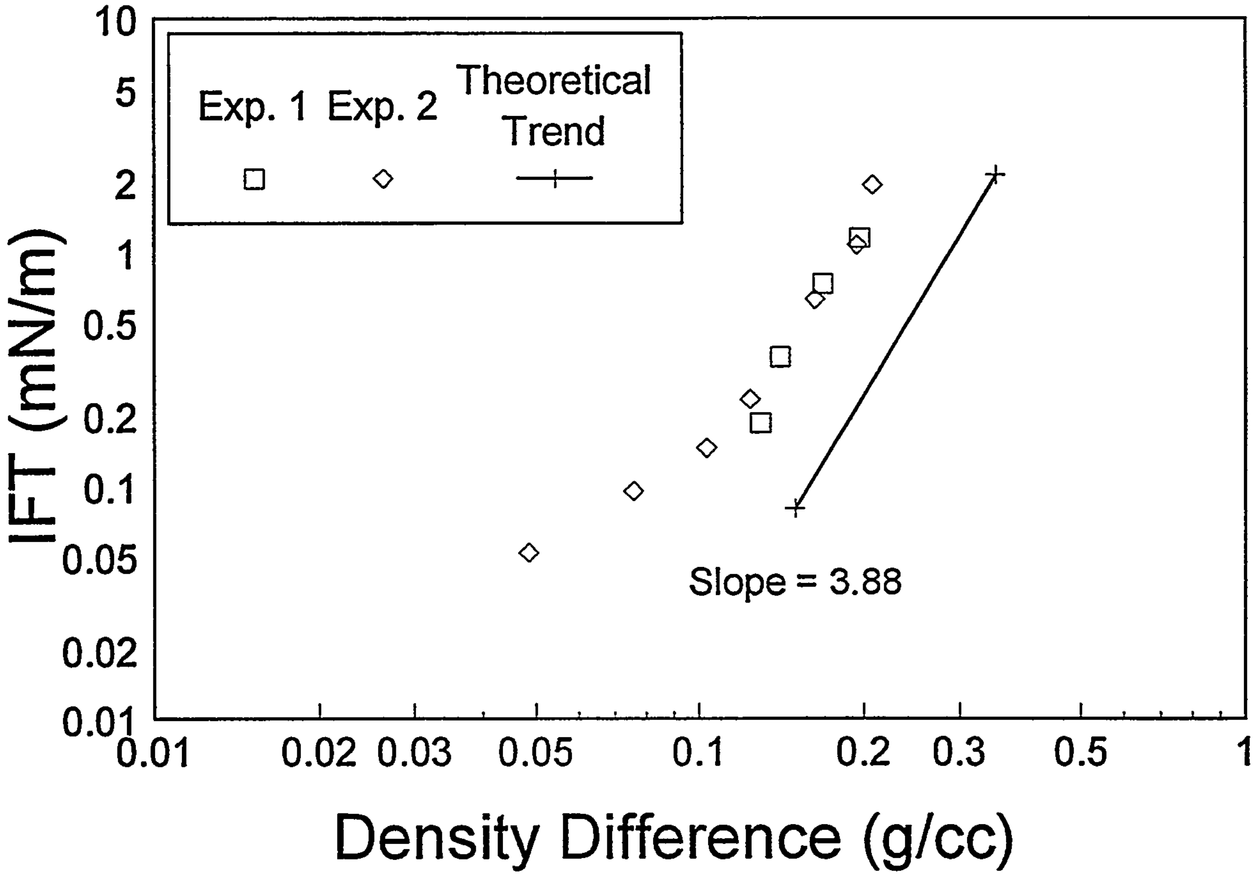

Figure 3. IFT vs. density difference for brine/heptane/isopropanol system.

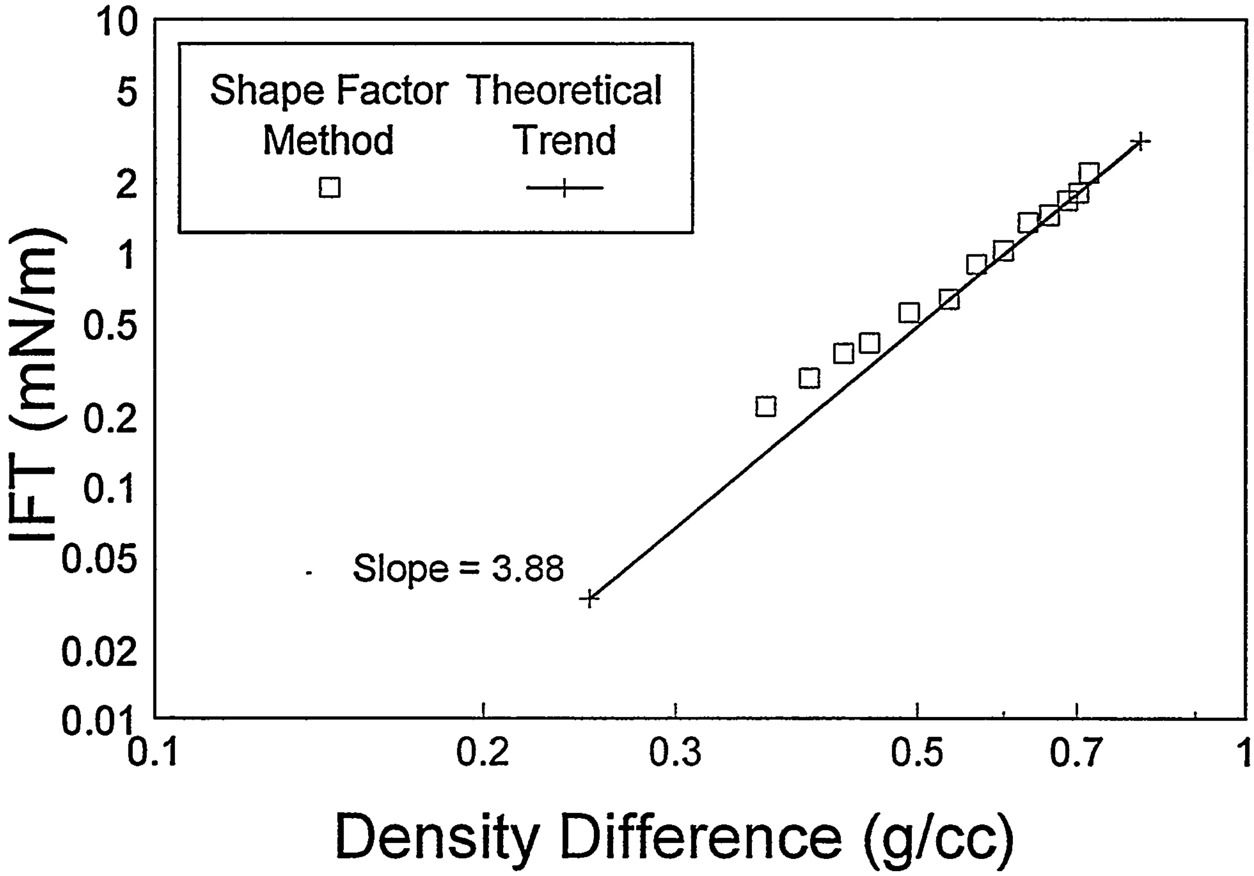

Figure 4. IFT vs. density difference for CO_2, minimizing change in experimental conditions between test points.

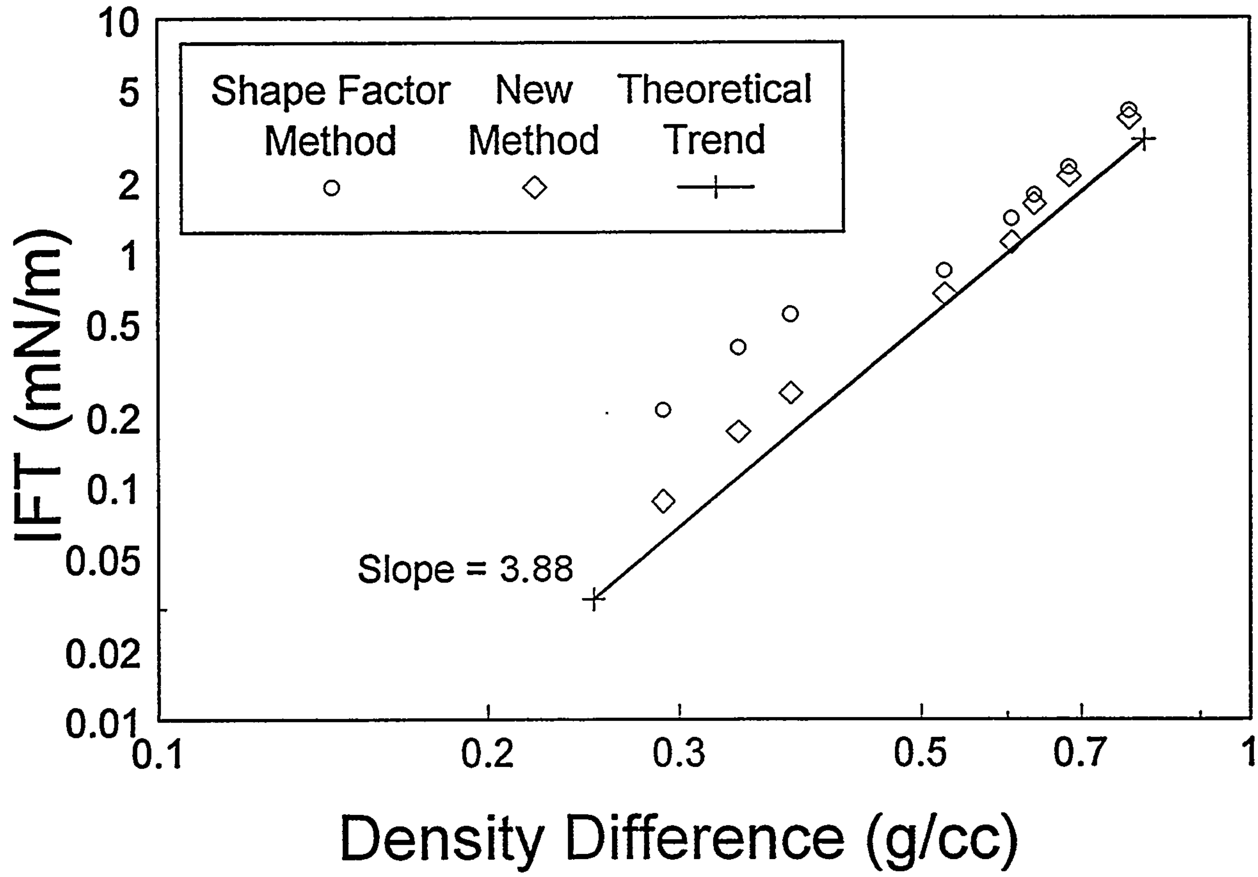

Figure 5. Comparison of new method and shape factor method.