MEASUREMENT AND MODELING OF GAS-OIL MISCIBILITY FOR IMPROVED OIL RECOVERY

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ABSTRACT

Laboratory measurement as well as modeling of gas-oil miscibility conditions are essential for success of any gas injection improved oil recovery process in the field. The conventional slim-tube technique currently used by industry for gas-oil miscibility evaluation is time consuming (4-5 weeks) and is not cost-effective. However, recently a new experimental technique of vanishing interfacial tension (VIT) has been reported, relating miscibility with interfacial tension. This technique is based on the concept that, at miscibility, the value of interfacial tension between the two phases is zero. This new technique, being rapid, enables cost-effective determination of gas-oil miscibility.

In this paper, we discuss the experimental measurements of gas-oil miscibility conditions determined using the VIT technique for a simple standard gas-oil system as well as for a complex real crude oil-solvent system. The gas-oil interfacial tension measurements reported in this study were made using the pendent drop shape analysis and capillary rise techniques. The paper also provides experimental validation for VIT technique by comparing the results of gas-oil miscibility with the other conventional techniques. The gas-oil miscibilties measured were effectively modeled in both the systems studied, using the mechanistic modification of Parachor model for mass transfer effects. This study thus demonstrates the usefulness of a new technique, with supporting experimental data and modeling results, for optimization of miscibility conditions in gas injection improved oil recovery field projects.

1. INTRODUCTION

Miscible CO_2 gas injection has become one of the most effective improved oil recovery (IOR) processes for light and medium oil reservoirs in United States today. Out of 1581 large reservoirs covering almost all the ten basins in US, 1035 reservoirs have been screened to be favorable for implementing CO_2 gas injection IOR (Advanced Resources International, 2006). Among these 1035 reservoirs, about 900 reservoirs are concluded to be amenable for miscible CO_2 gas injection IOR. This clearly shows the growing importance of miscible CO_2 gas injection in the US IOR scenario. There is about 374 billion barrels of trapped crude oil in depleted oil fields in the US alone and it is possible to recover about 160 billion barrels of this trapped oil using the CO_2 IOR technology

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(Advanced Resources International, 2006). The worldwide target trapped oil for IOR is estimated to be about 2 trillion barrels (Moritis, 2004). However, the design of these miscible CO_2 gas injection IOR projects in the field requires the knowledge of the minimum miscibility pressure (MMP) or minimum miscibility enrichment (MME) to recover most of the oil in the gas swept zone of crude oil reservoirs. Hence prior laboratory evaluation and modeling of gas-oil miscibility conditions play a crucial role in any miscible gas injection IOR field study.

The primarily available experimental techniques to determine miscibility under reservoir conditions are the slim-tube displacement, rising-bubble apparatus and the pressure-composition diagrams. Among these, slim-tube technique is presently considered as the "petroleum industry standard" to determine gas-oil miscibility. In this technique, miscibility is indirectly determined from oil recovery. However, there exists neither a standard design, nor a standard operating procedure, nor a standard set of criteria for determining miscibility in slim-tube tests (Elsharkawy et al., 1996). Moreover, the definition of miscibility as the break-over point in the oil recovery versus pressure curve makes it essential to run several slow rate slim-tube displacement tests and hence this technique is costly and time consuming (4-5 weeks).

The fundamental definition of miscibility is the absence of an interface between the fluid phases, that is, the value of interfacial tension between the two phases is zero (Benham et al., 1965; Stalkup, 1983; Holm, 1987; Lake, 1989). To overcome the disadvantages associated with the conventional miscibility measurement techniques, the experimental technique of vanishing interfacial tension (VIT) has been developed based on this fundamental definition. In this method, the gas-oil interfacial tension is measured at reservoir temperature and at varying pressures or enrichment levels of gas phase. The gas-oil miscibility conditions are then determined by extrapolating the plot of interfacial tension against pressure or enrichment to zero interfacial tension. The summary of comparative evaluation of VIT technique against other conventional techniques (slim-tube and rising-bubble) is provided in Table 1. As can be seen in Table 1, this technique is cheaper, less time-consuming (1-2 days) and consumes fewer amounts of fluids compared to the other techniques. This technique is also capable of providing accurate miscibility results even at extreme operating conditions of temperature and pressure (20,000 psi and 400^oF).

The objectives of this study are therefore to demonstrate the usefulness of this VIT technique in gas-oil miscible field applications by conducting gas-oil interfacial tension measurements in a simple standard gas-oil system as well as in a complex real crude oil-solvent system. The gas-oil interfacial tension measurements were made using the pendent drop shape analysis and capillary rise techniques at reservoir conditions. This paper also aims to provide experimental validation for VIT technique by comparing the results of VIT gas-oil miscibilties with the other conventional techniques and to model the VIT gas-oil miscibilties using our newly proposed mechanistic Parachor model. This mechanistic Parachor model was a modified version of conventional Parachor model, in which the ratio of diffusivity coefficients raised to an exponent was introduced to account for mass transfer effects. More details on the theory, background and equations involved in mechanistic Parachor model can be found elsewhere (Ayirala and Rao, 2006).

2. EXPERIMENTAL APPARATUS AND PROCEDURE

The Rainbow Keg River (RKR) live crude oil, various C_{2+} enrichments in hydrocarbon injection gases, live decane (consisting of 25 mole% n-methane, 30 mole% n-butane and 45 mole% n-decane) and CO_2 gas were used in the experiments. RKR live oil was prepared by adding appropriate amounts of light ends, n-methane to n-pentane, to RKR stocktank oil.

The gas-oil IFT measurements of RKR live crude oil at various C_{2+} enrichments in injection gas and at a pressure of 2150 psi and 190^oF were carried out using the drop shape analysis technique. The detailed description of the apparatus and the experimental procedures used for IFT measurements in this crude oil-gas system are provided elsewhere (Rao, 1997). A mixture consisting of 10 mole% of crude oil and 90 mole% of hydrocarbon gas is used as the feed composition during these experiments. The experimental apparatus consisted of a high-pressure and high-temperature optical cell capable of operating up to 10,000 psi and 400^oF. The cell was first filled with gas and the pendent drops of oil were formed in the surrounding gas using a capillary tip. The pendent drop images were then captured using a light source and digital camera. The captured images were analyzed for gas-oil interfacial tension using the axisymmetric drop shape analysis (ADSA) program (Rotenberg et al., 1983).

The schematic of the experimental apparatus used for gas-oil interfacial tension measurements in the live decane-CO_2 standard gas-oil system at 160^oF using the capillary rise technique is given in Figure 1. This apparatus consisted of a high-pressure high-temperature optical cell (has a design rating of 400^oF and 20,000 psi), in which the capillary tube is stationed, transfer vessel holding the oil, centrifugal pump, Ruska pump holding CO_2 gas and a PAAR DMA-512 density meter. IFT measurements were carried out using a molar composition of 80/20 mole% gas and oil in the mixture in this standard gas-oil system. More details on the procedure as well as the equations used for IFT calculations in capillary rise technique can be found elsewhere (Ayirala et al., 2006).

3. RESULTS AND DISCUSSION

3.1 Rain bow Keg River Crude Oil-Gas System

The gas-oil interfacial tensions measured at various C_{2+} enrichments in gas phase at a reservoir temperature of 190^oF in this crude oil-gas system are shown in Figure 2. The extrapolation of the linear trend line, fitted to all the experimental values, to zero IFT gives a VIT minimum miscible composition (MMC) of 51.2 mole% C_{2+} enrichment in the gas phase. The coefficient of determination (R^2) of 99.4% obtained indicates a good fit. The measured gas-oil interfacial tensions were later modeled using the new mechanistic Parachor model. These modeling results are also summarized in Figure 2. A good match of IFT measurements with model predictions can be seen in Figure 2. The gas-oil interfacial tension predictions from the mechanistic Parachor model were also fitted using linear regression and the extrapolation of this trend line to zero IFT gives 54.4 mole% C_{2+} enrichment in the gas phase to be the VIT MMC. This equation also has a coefficient of determination (R^2) of 99.6% indicating a good fit. Thus the predicted VIT miscibility deviated by only about 6.2% from the measured VIT miscibility in this gas-oil system, which validates the new mechanistic Parachor model to predict miscibility in crude oil-gas systems.

3.2 Live Decane-CO_2 System

This standard gas-oil system has been reported to have a slim-tube minimum miscibility pressure of 1685 psi at 160^{o}F (Metcalfe and Yarborough, 1979). The summary of interfacial tensions measured in this gas-oil system at 160^{o}F and at various pressures is shown in Figure 3. The IFT measurements were fitted against pressure using a hyperbolic function, which when extrapolated to zero IFT yielded a minimum miscibility pressure (MMP) of 1764 psi. This VIT miscibility agreed well with the reported slim-tube miscibility (1685 psi). Thus, this VIT experiment, conducted using the standard gas-oil system of live decane-CO_2 at 160^{o}F, provides experimental validation for the VIT technique to measure gas-oil miscibility.

The comparison between the measured as well as the predicted gas-oil interfacial tensions using the mechanistic Parachor model for live decane-CO_2 system is shown in Figure 3. From Figure 3, a good match of IFT predictions from the mechanistic model with IFT measurements can be seen even in this gas-oil system. The mechanistic model IFT predictions were fitted against pressure using the hyperbolic function and the relationship obtained is also shown in Figure 3. The extrapolation of this relationship to zero IFT gives a predicted VIT miscibility pressure of 1758 psi. This predicted VIT miscibility is almost identical to the experimentally measured VIT miscibility (1764 psi) and deviates by only about 0.3%. The relatively inadequate regression fits obtained using the hyperbolic function for experimental as well as predicted IFT data in Figure 3 are due to nearly two orders of magnitude reduction in IFT observed near miscibility. However, it is interesting to note that the hyperbolic functions used are well fitting the data in the low IFT regions, which is critical for VIT miscibility determination. Other regression fits using the exponential function may better describe the data over the entire IFT range, but they cannot be extrapolated to zero and hence need to define interfacial tensions in the range of 10^{-6} to 10^{-8} mN/m to achieve miscibility.

The slight deviations obtained between the experimental and predicted IFT data in the two gas-oil systems studied can be attributed to the difficulty in predicting interfacial tension in multicomponent complex crude oil-gas systems. However, these deviations in interfacial tension observed have little effect on miscibility thereby leading to accurate miscibility predictions by the mechanistic Parachor model.

The VIT technique is capable of providing accurate miscibility results even in the cases of asphalente precipitation, which is accounted for by the dual rate decline of gas-oil interfacial tension (Rao, 1997). However, slim-tube miscibility results for crude oil-gas systems with asphaltene precipitation effects are doubtful. Another often mentioned advantage of slim-tube technique is that it yields oil recovery factors. However, as Stalkup (1983) cautions, “it does not simulate many aspects of reservoir flooding, and the levels of ultimate recovery, both for immiscible and for miscible tests, should not be considered as indicative of the unit displacement efficiency to expect in reservoir rocks”.

4. SUMMARY AND CONCLUSIONS

Gas-oil interfacial tension measurements were carried out in a complex crude oil-gas system as well as in a simple standard gas-oil system at reservoir conditions. The close match of VIT miscibility obtained in the standard gas-oil system with slim-tube miscibility validates the VIT technique to determine gas-oil miscibility. The gas-oil interfacial tensions were modeled using the newly proposed mechanistic Parachor model in both the gas-oil systems and the predicted VIT miscibilities from the model agreed well with the measured VIT miscibilities. This study has thus validated a new experimental technique and resulted in a new computational model, both of which have potential use in quick and cost-effective optimization of miscibility conditions for gas injection improved oil recovery field projects.

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Table 1. Comparative Evaluation of Various Miscibility Measurement Techniques

Criteria	Slim-Tube	Rising-Bubble	Vanishing Interfacial Tension
How widely the technique is used?	Industry standard and hence widely used	Only used for reasonable and quick estimates	Recently developed and hence not yet widely used
Does the technique satisfy the fundamental definition of miscibility as zero IFT?	No	No	Yes
What is the miscibility determining criterion?	Oil recovery	Visual observations of gas bubble behavior	Zero gas-oil IFT
Is there a fixed design and standard set of criteria?	No	Yes	Yes
What are the pressure and temperature limits?	10,000 psi and 300°F	10,000 psi and 300°F	20,000 psi and 400°F
What quantities of fluids are required?	500 - 3000 cc of oil 1000 - 5000 cc of gas	300 - 800 cc of oil 100 - 200 cc of gas	100 - 200 cc of oil 200 - 400 cc of gas
What are the costs involved?	$ 10,000 - $ 25,000	$ 2,000 - $ 4,000	$ 2,500 - $ 5,000
How much time is needed?	4 - 5 weeks	5 - 6 hours	1 - 2 days
Is the technqiue qualitative or quantitative?	Quantitative	Qualitative	Quantitative
Is the technqiue reliable and accurate?	Yes	No	Yes

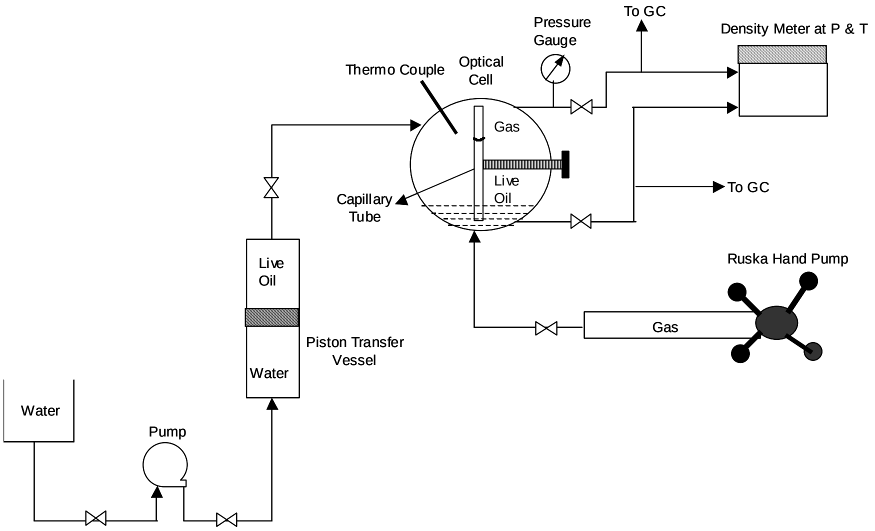

Figure 1. Schematic of the Experimental Apparatus Used for IFT Measurements in Live Decane-CO_2 Standard Gas-Oil System at 160°F

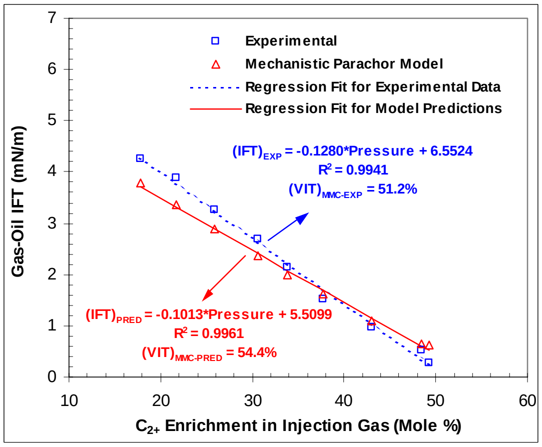

Figure 2. Comparison of Experimental and Predicted VIT miscibilities in RKR Crude Oil-Gas System

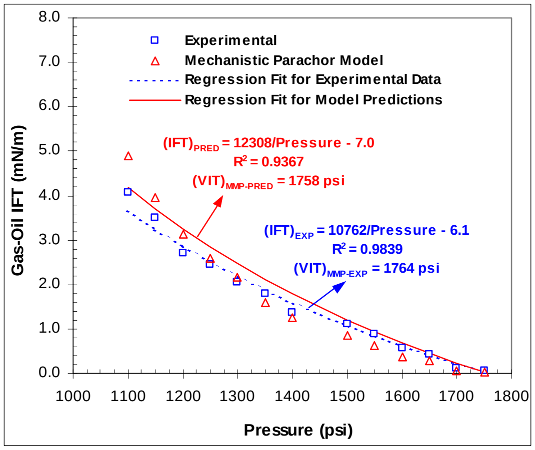

Figure 3. Comparison of Experimental and Predicted VIT miscibilities in Live Decane-CO_2 System