Effect of CO$_2$/N$_2$ Mixture Composition on Interfacial Tension of Crude Oil

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ABSTRACT: CO$_2$-enhanced oil recovery (EOR) has demonstrated significant success over the last decades; it is one of the fastest-growing EOR techniques in the USA accounting for nearly 6% of oil production. A large quantity of CO$_2$ gas is required for the EOR process and sometimes other gases such as hydrocarbons, air, flue gases, CO$_2$, N$_2$, and mixtures of two or more gases are used for injection. It is also realized that the injection of CO$_2$ and N$_2$ combines advantage in reducing CO$_2$ concentrations in the atmosphere and improving the oil recovery by sequestering it underground. However, there are a number of variables involved in the successful design of the CO$_2$-EOR process. The objective of this study is to investigate the effect of CO$_2$/N$_2$ mixture composition on interfacial tension (IFT) of crude oil. Experiments were performed to measure the IFT of the CO$_2$/N$_2$ mixtures and crude oil for different compositions of gas by varying the system pressure at a fixed temperature. The effect of CO$_2$/N$_2$ mixture composition and pressure on the IFT of crude oil is evaluated. The experimental results show that an increase in the mole fraction of CO$_2$ in the gas mixture results in a decrease in IFT between CO$_2$—oil, irrespective of the system pressure. However, because of an increase in the mole fraction of N$_2$ in the gas mixture, an increase in IFT was observed and this change is opposite to the effect of the CO$_2$ mole fraction. Also, the change in IFT is consistent with the pressure, which means that the IFT decreases with an increase in the pressure at a given temperature. The effect of the CO$_2$ mole fraction is more profound compared to the N$_2$ fraction and with the pressure at which experiments were conducted in this study. The finding of this study helps in designing the CO$_2$-EOR process in which achieving miscibility conditions is vital for taking advantage of the CO$_2$ injection. Also, the presence of N$_2$ and its influence on the IFT that must be considered in the CO$_2$-EOR were addressed in this study.

INTRODUCTION

As the major global energy provider, the oil and gas industry has faced many challenges to keep up with the increasing global demand. Because most major reservoirs have already been discovered and chances of finding new ones are very low, one of the options left to increase production is to increase recovery of the already producing reservoirs by implementing enhanced oil recovery (EOR) techniques. The implementation of EOR techniques is often necessary to maintain operations in reservoirs realizing depletion and declining production rates. In general, field operators consider two major factors during the design of enhanced recovery operations: technique practicability and economic viability. EOR techniques can be classified into three major categories: thermal, chemical, and gas injection (immiscible or miscible).

In gas injection techniques, various gases are injected into the reservoir such as hydrocarbons, air, flue gases, CO$_2$, N$_2$, and sometimes mixtures of two or more of the aforementioned gases. However, CO$_2$-EOR gained popularity because of several advantages associated with it such as CO$_2$ can be miscible with oil resulting in a reduction in oil viscosity, causing oil swelling, and lowering interfacial tension (IFT) under specific conditions of pressure, temperature, and oil composition. It can invade the zones that were not invaded by water before resulting in reducing and releasing trapped oil. Moreover, CO$_2$-EOR can be used to sequestrate large quantities of CO$_2$ in the reservoirs.

CO$_2$-EOR is accounting for nearly 6% of U.S. onshore oil production, around 350,000 barrels per day. By 2010, the number of CO$_2$-EOR projects around the world had reached 127, from which 112 projects are in the United States. This technique uses CO$_2$, both naturally occurring as well as a byproduct of industrial processes, to increase the production of oil from the existing oil fields. Although CO$_2$-EOR is already an important component of today’s oil production, it has great potential to expand production. An analysis commissioned by the U.S. Department of Energy (DOE) projects potential oil resources recoverable with CO$_2$-EOR of up to 137 billion barrels, with 67 billion barrels economically recoverable at $85 a barrel. This represents more than three times the current U.S. proven reserves. The Permian Basin is one of the most active
The IFT plays a vital role, especially in the EOR processes. Among the different EOR techniques, chemical/surfactant injection and gas injection which are aimed to reduce capillary pressure are governed by the resulting IFT because of the introduction of chemicals or gases in the reservoir. The lowering of the IFT is considered as one of the prime factors in the success of EOR. In the case of the gas injection process such as CO$_2$, the IFT dictates the schemes of the injection as whether the process is miscible or immiscible. Many studies utilized IFT as a parameter to study the interaction of gases such as CO$_2$, CH$_4$, and N$_2$ with water, crude oil, or n-decane. Also, IFT has been utilized for determining the miscibility or immiscibility condition of the CO$_2$-EOR processes.

There are different ways to measure the IFT that exists between the different phases such as pendant drop, capillary rise, Du Noüy ring, and slim tube. Each of these methods has its limitation and accuracy in the measurement of IFT. The measurement of IFT using the pendant drop method requires a high-density difference between different phases; however, the measurement is done under high-pressure conditions. One of the limitations of this method is that it is not suitable for the measurement of the very low value of IFT. On the other hand, the capillary rise measurement method can be utilized for the measuring low value of IFT. There are other factors that also influence the selection of IFT measurement methods. These factors are important especially dealing with the petroleum fluid, which is multicomponent in nature. The complex nature of the multicomponent system makes measurements of the IFT difficult; moreover, IFT measurement requires phase densities, which is difficult to obtain in the multicomponent systems. For example, for a system with low solubility (hydrocarbon + water) and (nitrogen + water) mixtures, the density of the saturated phases has been commonly approximated to that of pure substances. For the miscible system such as (carbon dioxide + water) and (carbon dioxide + n-alkanes), it further complicates the system leading to inaccurate estimation of the IFT.

The complexities associated with the measurement of IFT due to CO$_2$ interaction with oil or water and associated chemicals were addressed by measuring the dynamic IFT. Also, the effect of temperature and pressure was investigated on the dynamic IFT between the CO$_2$, crude oil, and water with different ionic compositions as well as in the presence of chemicals. However, there is no clear relationship between the CO$_2$ mole fraction and oil/brine IFT, as this physical property depends on complex intermolecular forces including electrostatic, acid–base, and other interactions.

The IFT investigations are not limited to laboratory measurement studies. There are studies on predictive and theoretical approaches for IFT that are presented in the literature. Among the different approaches, one of the simplest and commonly used approaches is presented by Parachor. However, it is not suitable for many systems such as IFT calculation of the CH$_4$ + H$_2$O system. Another theoretical approach is the density gradient theory (DGT), and linear gradient theory (LGT) is available for predicting the IFT values of the system. Moreover, studies pertaining to the assessment of the theoretical models with the laboratory measurement were carried out by the investigators. However, the DGT and LGT have not been widely tested for the IFT between gas mixtures because of the unavailability of the data in the literature. A more rigorous approach through integrated experimental measurements is required for validation of the theoretical and predictive models.

There are studies on understanding the phase behavior and to predict the saturated densities of CO$_2$, N$_2$, and CH$_4$ with n-decane presented in the literature, which can be correlated with the IFT as the density of the phases in contact is essential for the estimation of IFT. Also, the effect of the pressure and temperature on the densities of saturated phases was investigated to have accurate models for IFT. The experimental investigation of the IFT in these systems was investigated only for the pure system. Moreover, some studies were carried out in relation to the gas solubility in the oil, as well as IFT of the gas mixture with water. Despite all studies conducted to better understand IFT, only a few were concerned with the effect of gas composition on the IFT between gas and oil. A study performed on North Sea oils was concerned with nitrogen/oil IFT and conclusions were made that the developed method was not sufficient for accurate predictions because of...
large deviations from experimental values.\textsuperscript{80,81} It arises a need for further investigation to be concerned with the effect of gas composition on oil surface tension. Therefore, this study aims to investigate the effect of gas composition on the IFT of crude oil by subjecting crude oil samples to gas mixtures of different CO\textsubscript{2} and N\textsubscript{2} ratios in a range of pressures. The IFT properties of the gas mixture with oil were not investigated in the literature, especially, when the mixture of gases contains the components with wide variation in the properties such as solubility as well as phase behavior. This study attempts to fulfill this gap by evaluating the effect of gas composition on the IFT of crude oil in a wide range of pressure conditions through experimental measurement of the IFT of crude oil with the gas mixture.

\section*{METHODOLOGY}

The effect of CO\textsubscript{2}/N\textsubscript{2} mixture composition on IFT of crude oil was evaluated by performing a series of experiments by measuring gas–oil IFT with the pendant drop technique. The IFT measurement was performed for different compositions of the gas mixture under a specific condition of pressure and temperature. Attention was given to the composition of injection gas to determine its effect on IFT during the interaction between injected gas mixture composition and crude oil. The following sections explain the details of the experimental setup, materials, and procedure used in the study.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{(A) Experimental setup used in the IFT measurement of crude oil and gas mixture. (B) Schematic of the setup used in the IFT measurement of crude oil and gas mixture.}
\end{figure}

\textbf{Experimental Setup.} The experimental apparatus used in the study is manufactured by Vinci Technologies IFT Meter (IFT 700). The apparatus is designed to withstand high pressure (10,000 psi) and a high temperature of 356 °F (180 °C). It can measure the IFT in the range of 0.1–72 mN/m by drop shape analysis. To facilitate the variation in the composition of the gas mixture, additional gas accumulator, syringe pump, and pressure gauges were installed to modify the system as shown in Figure 1A,B, schematic of the experimental setup. The modified system enables to measure the IFT of crude oil with variation in gas mixture composition over a range of pressure and temperature conditions. The composition variation of the gas mixture is achieved by injecting the particular gas in the cell under a controlled pressure condition.

\textbf{Materials.} The materials used in the study are

1. CO\textsubscript{2} gas (99.99% purity), supplied from Saudi Industrial Gas Company
2. N\textsubscript{2} gas (99.99% purity), supplied from Saudi Industrial Gas Company
3. Arab light oil (API 40)

\textbf{Procedure.} The following steps were involved in the experimental work.

1. The oil density was measured as a function of temperature, and correlations were utilized to determine its value at various pressures.
2. The gas mixture densities were determined at each value of pressure and temperature using the correlation.

3. The equipment was made ready for the experimental runs under the specific condition of pressure, temperature, and gas mixture, each experiment was performed, and IFT data were collected for the analysis.

4. Two different sets of experiments were performed in this work. First, the IFT measurements were carried out by fixing the gas mixture composition and the pressure was changed from low to high value until the lowest value of IFT is recorded. The composition of the gas mixture at a specific value of pressure is maintained using the gas compressibility factor.

5. In the second set of experiments, the pressure was increased by the injection of N\textsubscript{2} gas in a cell which is filled with CO\textsubscript{2} at a particular pressure. The resultant gas composition is determined using real gas law for specific pressure at which IFT is measured. A similar procedure was repeated by injecting CO\textsubscript{2} gas in a cell filled with N\textsubscript{2} at a particular pressure. The resultant gas composition is determined using real gas law, and IFT measurement is performed at a specific value of pressure.

6. The IFT measurement was performed using the pendant drop method. Initially, all the traces of the oil and impurities were removed from all eight tubing connections and from the visual cell. Then, oil is transferred to the oil accumulator from which oil is injected into the cell for creating the pendant drop in the presence of the gas phase. The gas phases are injected into the visual cell from the accumulator connected to the syringe pump to provide the required pressure and the composition of the gas mixture is controlled by controlling the pressure of the individual gas phase. After starting the software, the gas and oil densities as well as the required temperatures are set through the software and the equipment is left to stabilize for the temperature. Then, the oil is carefully displaced from the drop chamber through the connections until it comes out of the needle as a hanging droplet inside the gas-filled chamber. The equipment automatically records the readings. After the reading is stabilized and enough data points are recorded, the pressure can be changed to perform a new experiment.

7. The result was analyzed to evaluate the effect of gas composition on gas–oil IFT as a function of pressure at a fixed value of temperature.

## RESULTS AND DISCUSSION

### Density of Oil

Initially, the density of the oil is measured at 77 °F (25 °C) using a densitometer. Considering this measurement as a base value of the oil density, Standing—Katz correlation is used to obtain the value of the oil density for a different set of experimental conditions. Considering that oil density (dead oil) does not vary significantly as a function of pressure, the densities for different values of pressure were determined. Table 1 shows the oil density as a function of temperature. For oil density determination, the Standing—Katz method was used.

Standing—Katz correlation for oil density

\[ \rho_o = \rho_{oo} + \Delta \rho_p - \Delta \rho_T \]

### Density of the Gas Phase

The density of the gas phase (mixture of CO\textsubscript{2}/N\textsubscript{2}) was determined for a particular set of the experimental condition by determining the corresponding values of compressibility using Papay’s correlation and applying the Kays mixing rule to obtain the density of the gas mixture as a function of composition, pressure, and temperature.\(^{27}\) The density of the 80% CO\textsubscript{2} and 20% N\textsubscript{2} at 25 °C for different values of pressure is shown in Table 2.

### IFT of the Oil and Gas Mixture

To evaluate the effect of gas composition on gas–oil IFT, five experiments for the various gas compositions and at a different value of pressure were carried out. The first experiment was carried out to determine the IFT of the CO\textsubscript{2} gas as a function of pressure by keeping the temperature constant at 77 °F (25 °C). In the second experiment, the ratio of CO\textsubscript{2}/N\textsubscript{2} was kept constant at 80:20, and IFT was determined as a function of pressure by keeping the temperature constant at 77 °F (25 °C). Similarly, a third experiment was performed for the ratio of CO\textsubscript{2}/N\textsubscript{2} as 50:50 and IFT was determined as a function of pressure by keeping the temperature constant at 77 °F (25 °C). The fourth and fifth experiments were performed by varying both composition and pressure of the system at a constant temperature of 77 °F (25 °C).

It should be noted that for the IFT measurement, densities of the pure phases were used instead of equilibrium densities of the oil-dominated liquid phase and gas mixture-dominated vapor phase. The phase densities are difficult to obtain for the multicomponent system. The phase densities were not measured, as a high-pressure high-temperature densitometer was not accessible. Also, the density of the oil with dissolved CO\textsubscript{2} is assumed to be constant, as variations of the oil density

### Table 1. Density of Oil as a Function of Pressure and Temperature

| temperature (°F (°C)) | pressure (psia) | \( \Delta \rho_p \) (lb/ft\(^3\)) | \( \Delta \rho_T \) (lb/ft\(^3\)) | oil density (lb/ft\(^3\)) | oil density (g/cm\(^3\)) |
|------------------------|----------------|------------------------------|------------------------------|-----------------------------|-----------------------------|
| 77 (25)                | 14.7           | 0                            | 0.35                         | 51.10                       | 0.819                       |
|                        | 250            | 0.05                         | 0.35                         | 51.15                       | 0.820                       |
|                        | 500            | 0.1                          | 0.35                         | 51.20                       | 0.821                       |
|                        | 600            | 0.12                         | 0.35                         | 51.22                       | 0.821                       |
|                        | 750            | 0.15                         | 0.35                         | 51.25                       | 0.822                       |
|                        | 1000           | 0.2                          | 0.35                         | 51.30                       | 0.822                       |
|                        | 1250           | 0.25                         | 0.35                         | 51.35                       | 0.823                       |
|                        | 1500           | 0.3                          | 0.35                         | 51.40                       | 0.824                       |

### Table 2. Gas Mixture (80% CO\textsubscript{2} and 20% N\textsubscript{2}) Density as a Function of Pressure at 77 °F (25 °C)

| pressure (psia) | temperature 77 °F (536 °R) | gas mixture density (lb/ft\(^3\)) | gas mixture density (g/cm\(^3\)) |
|----------------|-----------------------------|---------------------------------|---------------------------------|
| 14.7           | 0.014                       | 1.030                           | 0.995                           | 0.072                         | 0.0012                       |
| 250            | 0.244                       | 0.918                           | 1.324                           | 2.890                         | 0.0465                       |
| 500            | 0.489                       | 0.841                           | 4.742                           | 6.932                         | 0.1115                       |
| 750            | 0.733                       | 0.769                           | 9.318                           | 16.144                        | 0.2596                       |
| 1000           | 0.978                       | 0.701                           | 15.38                           | 24.13                         | 0.3562                       |
| 1250           | 1.222                       | 0.639                           | 22.22                           | 34.84                         | 0.4247                       |
| 1500           | 1.467                       | 0.580                           | 29.16                           | 45.26                         | 0.5014                       |
| 1750           | 1.711                       | 0.527                           | 36.09                           | 55.70                         | 0.5772                       |
| 2000           | 1.955                       | 0.478                           | 43.02                           | 66.13                         | 0.6523                       |

Papay’s correlation for the compressibility factor

\[ Z = 1 - \frac{3.53P_{pr}}{10^{0.9813 P_{pr} T_{pr}}} + \frac{0.2747P_{pr}^2}{10^{0.8157 P_{pr} T_{pr}}} \]

IFT of the Oil and Gas Mixture. To evaluate the effect of gas composition on gas–oil IFT, five experiments for the various gas compositions and at a different value of pressure were carried out. The first experiment was carried out to determine the IFT of the CO\textsubscript{2} gas as a function of pressure by keeping the temperature constant at 77 °F (25 °C). In the second experiment, the ratio of CO\textsubscript{2}/N\textsubscript{2} was kept constant at 80:20, and IFT was determined as a function of pressure by keeping the temperature constant at 77 °F (25 °C). Similarly, a third experiment was performed for the ratio of CO\textsubscript{2}/N\textsubscript{2} as 50:50 and IFT was determined as a function of pressure by keeping the temperature constant at 77 °F (25 °C). The fourth and fifth experiments were performed by varying both composition and pressure of the system at a constant temperature of 77 °F (25 °C).
with the CO₂ dissolution at these pressures are minimal. It may lead to variation in the measured value of IFT from the actual IFT value. The average IFT values based on the shape of the captured pendant drop at the equilibrium pressure and temperature are reported in this paper. Similar results were also reported for other crude oil/CO₂ systems in the literature.79−85

**CO₂/Oil Equilibrium IFT (Experiment 1).** In this experiment, the IFT was measured for the pure CO₂ system by keeping the temperature constant at 77 °F (25 °C) and pressure was increased from the lowest value until it reaches the stage where the pendant drop is unable to form within equilibrium with CO₂. This point refers to the maximum pressure at which IFT can be measured with the pendant drop method. The results are shown in Figure 2. As can be seen that for the oil utilized in this study that has IFT 16.58 ± 0.38 measured at the lowest pressure (250 psi), the pendant drop method can be used to measure the value of IFT for the pure CO₂ up to a pressure of 750 psi (IFT = 7.6 ± 0.11) for the oil used in this study. The IFT decreases with an increase in pressure of the system, and similar results were presented in the literature in which IFT decreases with an increase in the system pressure.39,45,47,48 For the comparison, the IFT measurement of pure CO₂ with crude oil was presented from the study by Yang and Gu.9 In the study by Yang and Gu, the density of the oil was assumed to be constant, and the small variation due to CO₂ dissolution in oil was not accounted for the IFT measurement. The density of the CO₂ was calculated at a particular temperature and pressure condition of IFT measurement. Similarly, in the present study, the gas densities were calculated based on the densities of the pure component system; however, the density of oil was corrected for the pressure and temperature condition. It can be seen that trends of IFT with pressure are comparable, in which IFT is decreased with an increase in pressure. The IFT of the pure CO₂ at higher pressure is not feasible with the pendant drop method, which is based on the drop shape analysis, and required drop shape, which is unable to form at high pressure (850 and 950 psi), as shown in Figure 3. Similar phenomena were observed in several studies on IFT of CO₂ with liquid hydrocarbon.13,84−87

**IFT of the CO₂/N₂ (80:20) Mixture with Crude Oil (Experiment 2).** The second experiment was performed with a CO₂-rich gas mixture; it represents the case of some quantity of impurities present in the CO₂ gas during the CO₂-EOR process. The IFT was measured for the CO₂/N₂ (80:20) gas mixture equilibrium with crude oil by keeping the temperature constant at 77 °F (25 °C) and the pressure was increased from the lowest value until it reaches the stage where the pendant drop is unable to form in the presence of the CO₂/N₂ (80:20) gas mixture in equilibrium with crude oil. The results are shown in Figure 4. It can be seen that the IFT of the system is increased with the addition of N₂ to the CO₂. The change in IFT is not significant and it might be due to the small quantity of N₂ present in the system. Also, the pendant drop was able to form at higher pressure (900 psi) compared to the pure CO₂ (750 psi), and it indicates that the addition of N₂ gas to the CO₂ system leads to an increase in the miscibility pressure of the system.

**IFT of the CO₂/N₂ (50:50) Mixture with Crude Oil (Experiment 3).** In this experiment, the percentage of N₂ increased to 50%, and it will further affirm the effect of N₂ addition on the IFT of the system. It represents the case of gas injection operations that use carbon dioxide (CO₂) and nitrogen (N₂) mixtures in a cyclic gas injection process. The IFT was measured for the CO₂/N₂ (50:50) gas mixture equilibrium with crude oil by keeping the temperature constant at 77 °F (25 °C) and pressure was increased from the lowest value until it reaches the stage where the pendant drop is unable to form in the presence of the CO₂/N₂ (50:50) gas mixture in equilibrium with crude oil. The results are shown in Figure 5. It can be seen that the IFT of the system is increased with the addition of N₂ to the CO₂. The change in IFT is significant because of the reasonable
quantity of N₂ present in the system. Also, the pendant drop was able to form at higher pressure (1000 psi) compared to the pure CO₂ (750 psi), and it indicates that the increase in the percentage of the N₂ gas to the CO₂ system increases the miscibility pressure of the system. The IFT comparison for the pure CO₂, gas mixture CO₂/N₂ (80:20), and gas mixture CO₂/N₂ (50:50) is shown in Figure 6.

**IFT Behavior with an Increase in the N₂ Gas Fraction (Experiment 4).** In this experiment, initially, CO₂ is charged into the cell at low pressure. Then, the N₂ gas is introduced into the cell at a predetermined value of pressure by controlling the valve. The introduction of N₂ gas in the visual cell reduces the CO₂ gas fraction and subsequently increases the N₂ gas fraction in the visual cell. In each step, pressure and N₂ gas fraction increase (reduction in CO₂ gas fraction) in the system. The results are shown in Figure 7. It can be observed that the IFT of the system decreases with an increase in the N₂ gas fraction, which corresponds to an increase in the N₂ gas fraction in the system. In other words, a decrease in the N₂ gas fraction results in an increase in the IFT with crude oil, which is opposite to the effect of CO₂ gas. Similar to previous experiments, for the constant gas composition, the IFT decreases with an increase in pressure of the system. Also, in this experiment, IFT of the pure N₂ gas is measured at 200 psi which is the highest (∼21 mN/m) for all the range of IFT observed in this study. Similarly, the IFT for the CO₂/N₂ (∼90:10) ratio is ∼3.63 mN/m at 900 psi, lowest in the range of IFT measurement performed in this study.

**CONCLUSIONS**

In this study, rigorous experiments were carried out to evaluate the effect of gas composition on the IFT of crude oil. The constant gas composition (for pure CO₂ and CO₂/N₂ ratio of 80:20 and 50:50) IFT was measured as a function of pressure. Also, the IFT was measured by varying the fraction of individual
gas from ~10% to nearly ~90% along with ~99.99% pure form of the gases with maximum pressure (1000 psi) allowed by the system. The following are the conclusion from this study.

1. The IFT between the crude oil and gas system is significantly affected by the composition gaseous phase. The IFT appears to be the strong function of the gas composition.

2. The change in IFT depends on the type of gas; for CO₂, IFT decreases with an increase in the fraction of CO₂ in the mixture of CO₂/N₂. However, for N₂, IFT increases with an increase in the fraction of N₂ which is opposite to the effect of CO₂ gas on IFT of the crude oil and CO₂/N₂ gas mixture.

3. The IFT decreases with an increase in pressure of the system irrespective of the gas composition. The addition of N₂ gas may affect the CO₂ miscibility pressure indicated by an increase in the IFT value. For the CO₂/N₂ gas mixture system, an increase in the CO₂ gas fraction may help in achieving the miscibility at a lower pressure; however, an increase in the N₂ gas fraction can worsen the miscibility of the gas mixture with oil. It should be noted that minimum miscibility pressure was not measured in this study. It can be referred as the zero value of IFT used in VIT.

4. The IFT does not show any hysteresis effect, and an increase in the CO₂ fraction or N₂ fraction gradually gives the same value of the IFT as long as gas composition remains constant at the equilibrium with the crude oil under the specific condition of pressure and temperature.

5. The results from this study are very useful in designing the CO₂-EOR as the determination of IFT is crucial for capillary pressure estimation and designing the EOR process. Similarly, IFT is a critical parameter to understand the fluid—fluid interaction (solubility) in the cyclic gas injection processes in which a mixture of gases was injected into the reservoir for improving recovery. In addition, knowing the IFT of the system is very important in multiphase flow and surface production facility designing.

**LIMITATIONS**

It is acknowledged that the density used in the measurement of the IFT is based on the pure component densities. The changes in the densities of the gaseous and liquid phases in the equilibrium due to the interaction of the gases especially the solubility of carbon dioxide were not considered because of the complex multicomponent system presented in the study. Also, one of the aspects of applying the results in a real reservoir in which water is present as the third phase was not considered as the equipment can measure the IFT between two phases. Although, the IFT in the presence of third phase (water saturated with CO₂) was reported in the literature, where IFT between the oil and CO₂-saturated water rather than IFT between the gaseous and oleic phase.

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**Notes**

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