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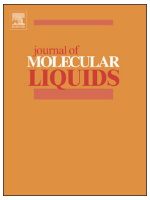

Experimental measurement of equilibrium interfacial tension of enriched miscible gas–crude oil systems

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ABSTRACT

During the design of an enhanced oil recovery (EOR) method in a particular gas flooding project, measuring interfacial tension between injected gas and live reservoir oil samples is essential for estimating optimum miscible gas injection scenarios at reservoir conditions. In this study, during an experimental miscible gas injection project for one of the Iranian oil fields, natural liquefied gas (NGL) and Naphtha were selected to enrich injecting gas in order to study the gas composition impact on efficiency of miscibility process. Therefore, injecting gas was enriched by recombining with NGL and Naphtha samples with predefined ratios. Afterward, an axisymmetric drop shape analysis (ADSA) was utilized to measure interfacial tension between reservoir oil and five synthesized gas samples at depletion pressure steps and constant reservoir temperature. The results showed the optimum miscible gas enrichment scenario with minimum interfacial tension at depletion pressure steps. Additionally, recombining injecting gas sample with NGL led to reduce interfacial tension more effectively than recombined samples with Naphtha. The results of this study are helpful for successful design of gas injection scenarios in this filed, and reveal the role of gas composition in the IFT behavior of crude oil systems.

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1. Introduction

As a partition of enhanced oil recovery (EOR) methods, gas flooding method includes carbon dioxide miscible injection, hydrocarbon miscible flooding, nitrogen miscible flooding and immiscible gas flooding. The main mechanism associated with miscible gas flooding method is the solvent extraction through miscibility by injection miscible gases [1]. As a result, gas flooding methods should be applied in deep reservoirs and the crude oil with high API and low viscosity. Therefore, accurately investigating the parameters affecting oil recovery is needed for the successful design of EOR techniques. As a matter of fact, interfacial tension (IFT) has an important role in any EOR technique, in particular gas flooding methods. In other words, the estimation of IFT at reservoir conditions is vital for selecting and designing of any gas flooding methods especially at reservoir conditions [2]. Furthermore, reliable measuring the IFT has been turned into a challenging topic in hydrocarbon reservoir fluid laboratories, thus accurate information on IFT is of vital significance in both petroleum and chemical engineering. When two different phases are in contact with each other, the molecules at the interface are forced with an imbalance of forces. This phenomenon results in an accumulation of free energy at the interface, which is determined by a property named IFT [3]. The importance of IFT may be magnified when dealing with EOR projects in which the relative magnitude of interfacial (capillary), gravitational and viscous forces significantly affects the recovery of hydrocarbons. In addition, the relative permeability, which determines the flow behavior of reservoir fluids in porous media, strongly depends on the interfacial tension. In other words, viscous forces, as a driving factor for mobilizing oil through porous media and capillary forces, as a trapping factor for retaining the reservoir oils within porous media compete with each other continuously through porous media. On the other hand, capillary forces are directly inspired by interfacial tension. Hence, measuring the IFT in different EOR techniques such as immiscible gas injection leads to finding a reliable estimate from capillary trapping forces at reservoir conditions [4]. Gas

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injection process affects the oil recovery by several mechanisms such as IFT reduction and wettability alteration of porous substrate. Lower IFT between gas and oil phases is favorable for enhancing oil recovery [5].

Distribution and location of gas and oil phases in a porous media are affected by the gas–oil IFT and wetting behavior of oil in the presence of gas. Generally speaking, the IFT and wettability are two of the most affecting parameters on permeabilities, capillary pressure, and oil remaining after drainage with gas [6]. Noticeably, the IFT behavior of crude oil–gas systems is strongly affected by thermodynamic conditions such as pressure and temperature. It is interesting to note that different gases show different IFT behaviors with crude oil. For instance, in crude oil–CO_2 systems, the IFT decreases with temperature at lower pressure, whereas it increases with temperature at higher pressure [7]. On the other hand, in crude oil–N_2 systems, the IFT decreases with temperature at all temperatures [2]. It can be concluded that the IFT behavior of crude oil with different gases should be carefully investigated. The hydrocarbon components with significant amounts of intermediate molecular weights (C_2–C_6) are applied as the composition of the injected fluid in enriched gas injection method. In other words, the components with intermediate molecular weight are condensed from the fluid injected into the reservoir oil making a band of enriched fluid, consequently adapting the composition of oil to become miscible with additional injected fluid [8].

A literature survey on previous works reported for interfacial tension indicates that an IFT equals to zero is an essential and adequate condition to reach miscibility [9–12]. Blanco and Ortega [13] reported liquid–vapor equilibrium data for the mixtures of methanol with n-pentane and n-hexane at pressure of 20.49 psia. Furthermore, they calculated/measured upper critical solubility for methanol, n-hexane mixtures from the reported miscibility data. Simon et al. [14] reported the interfacial tension related to a reservoir crude oil at different solvent–oil ratios in the feed utilizing a high-pressure interfacial tensiometer. The obtained results showed that interfacial tension depends on solvent–oil ratio in the feed. Consequently, by increasing the concentration of carbon dioxide gas available in the feed, the interfacial tension increases. Recently, Zolghadr et al. [15] measured the IFT of pure hydrocarbons (heptane and hexadecane)–CO_2 systems at various pressure conditions and temperature levels. The results showed that in such systems the IFT decreases linearly with pressure up to near miscibility conditions, at a constant temperature. Hemmati-Sarapardeh et al. [7] followed the work of Zolghadr et al. [15] and measured the equilibrium interfacial tension between two crude oils and CO_2 at different temperatures and pressures by using an axisymmetric drop shape analysis (ADSA). Moreover, they compared the results of crude oil–CO_2 systems with pure hydrocarbons–CO_2 systems. The results indicated that the IFT of crude oil–CO_2 reduces with temperature at low pressure conditions and increases with temperature at high pressure conditions. Additionally, they observed that paraffin content influences the IFT behavior of crude oil–CO_2 systems. In another studies conducted by Zolghadr et al. [16] and Hemmati-Sarapardeh et al. [2], they repeated the same procedure for the determination of equilibrium interfacial tension between pure hydrocarbon–N_2 systems and crude oil–N_2 systems, respectively. The results illustrated that the IFT reduces with temperature. Moreover, the interfacial tension reduces with pressure.

There are several other studies which reported IFT data of crude oil–gas systems; however, they are mostly for CO_2, N_2 and dry gases [17–19]. In addition, most of previously published works measured IFT of dead crude oils and IFT data of live crude oil systems are rarely available in the literature. To the best of the authors' knowledge, no work has yet been published on the IFT behavior of live crude oil–NGL and live crude oil–Naphtha systems. This work aims to study the impact of gas composition on the efficiency of miscibility process through an experimental miscible gas injection project for one of the Iranian oil fields. To this end, natural liquefied gas (NGL) and Naphtha were selected to pursue our objective in this study. Moreover, injecting gas was enriched by recombining NGL and Naphtha samples with predefined ratios. In other words, this study plans to measure interfacial tension between reservoir oil and five synthesized gas samples at depletion pressure steps and constant reservoir temperature.

2. Experimental section

2.1. IFT measurement by pendent drop method

IFT-700 System from Vinci Company was used for measuring surface tension (liquid–gas) and interfacial tension (liquid–liquid) using the pendant drop method (Laplace equation). Whole experimental set-up is depicted in Fig. 1. Different parts of Fig. 1 are as follows: (a) two pressure generators. (b) the stainless steel base. (c) the software for profile analysis. (d) two pressure indicators. and (e) the view chamber. The pendant drop method is defined as the formation of a liquid drop at the end of a hollow needle, which is submerged in a second bulk fluid. Drop formation is matured under constant temperature and pressure and the apparatus is mobilized with an accurate snapshot system. After taking a desired snapshot, a complete structure of the drop is analyzed with advanced drop shape analysis software. Using the drop dimensions on the achieved image and knowing the needle dimensions, the interfacial tension is determined precisely. More details about this experimental setup and IFT determination procedure can be found elsewhere [7,20]. It should be mentioned that maximum working pressure and temperature of IFT-700 are 10,000 psia and 300 °F, respectively (Figs. 2 and 3). In Fig. 2, (a) shows the view chamber and (b) is the video system.

2.2. Sample preparation

Reservoir oil sample in the pressure steps above the saturation pressure was monophonic, which could be injected through the needle in specified pressure and temperature precisely; but below the bubble point pressure, two different phases of liquid and gas were created. Hence, it was decided to design a differential vaporization test simultaneous with working on a pendant drop apparatus in order to prepare gas cap-released oil samples in pressure steps below the saturation pressure. To make a long story short during the differential vaporization test, the pressure of the live oil was fixed in predefined pressure steps and then evolved gas cap was removed from the top of the oil sample

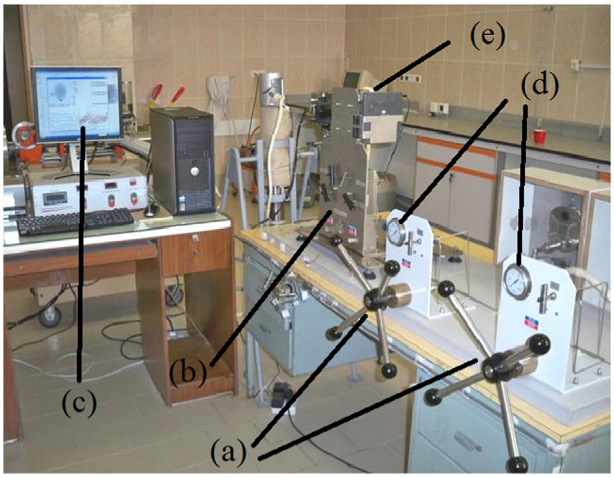

Fig. 1. The IFT experimental setup using Pendant drop technique.

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