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Toward mechanistic understanding of heavy crude oil/brine interfacial tension: The roles of salinity, temperature and pressure

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ABSTRACT

Injecting low salinity brines is regarded as an enhanced oil recovery (EOR) process through IFT reduction. However, the exact mechanism behind this process is an unsettled and complex issue that has not been well understood yet, especially for heavy crude oil system. Besides, limited information is available regarding the key heavy oil/brine interfacial tension (IFT). The present study aims to investigate the sensitivity of dead heavy crude oil/brine IFT to a wide range of properties/conditions and to reveal the underlying physicochemical mechanisms involved in enhanced oil recovery and IFT reduction by low salinity water injection into heavy oil reservoir. IFT was measured as a function of salinity, temperature, and pressure by means of the IFT 700 apparatus making available the use of the state-of-the-art axisymmetric drop shape analysis (ADSA) technique for the pendant drop case. Meanwhile, the individual effects of monovalent and divalent ions were also investigated.

The results indicate a conflict between salt and surface-active agents resulting in critical salt concentration where the IFT value is the minimum, beyond which brine dilution has a negative impact on IFT. In addition, our study illustrates that in all concentrations of salt, higher IFT values are obtained using $CaCl_2$ compared to NaCl aqueous solution, which is more intensive and apparent at higher concentrations. Furthermore, there is a strong inverse relationship between temperature and IFT, but a slightly increasing behavior with respect to pressure. The range of brine concentration in which the heavy oil/brine IFT is minimized is vital for successful design of low salinity water injection.

1. Introduction

Three different recovery stages from oil reservoirs have been introduced as “primary, secondary, and tertiary stages”. Natural reservoir pressure is the driving force in primary recovery phase. During the secondary recovery, water is normally injected into the reservoir to maintain and build up the pressure. The main part of the oil trapped after waterflooding is normally more than two third of the original oil in place mainly because of capillary and viscous forces [1–3]. In this stage, enhanced oil recovery (EOR) methods are used for more recovery efficiency from depleted oil reservoirs [4]. The ratio of viscous to capillary forces is described by a well-known dimensionless group called the capillary number [5]. Increasing the capillary number by changing the water and interfacial properties, in order to mobilize the trapped blobs, is referred to improved waterflooding as the tertiary oil recovery process [6–8]. Higher oil recovery during enhanced waterflooding could be achieved by either increasing the viscosity or decreasing the oil–water interfacial tension. Expensive polymer solutions with high value of injections pressures are normally flooded to increase viscosity, and therefore increase sweep efficiency, increasing viscosity involves the use of high pressures pumps which are very expensive and cause possible rock fracturing and channeling [9]; therefore, it would be more practical to focus on IFT reduction.

Earlier studies have demonstrated the importance of brine salinity in oil recovery by waterflooding [10]. Low salinity water injection has been proposed to reduce the interfacial tension between the reservoir oil and brine, the same as alkaline flooding [10,11], and furthermore increase oil recovery efficiency [12,13].

For the case of heavy crude oil, as the main remaining oil reservoirs for the oil consuming industry, the higher the viscosity of the oil, the more oil remains after natural water drive or secondary oil recovery technique, waterflooding [14]. The experimental results presented in the literature lack the case of heavy oil and brine to

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investigate the effects of salinity, temperature and pressure on the IFT. The focus of this study is to analyze the heavy crude oil/brine IFT and to understand the interactions that take place between brine and crude oil in the presence of impurities at various conditions of temperature, pressure and brine concentration using IFT 700 supplied by Vinci Company through ADSA technique.

2. Background

2.1. IFT measurement methods

Interfacial tension is defined as the free energy required per unit surface area of the interface between two phases and is related to Gibbs free energy as follows [15]:

$$dG = \gamma dA\,(\text{constant}\,T\,\&\,P) \quad (1)$$

where γ is the surface free energy per unit area (J/m^2) or force per unit length (N/m). Interfacial tension measurement can be accomplished by different methods, such as spinning drop [16], sessile drop [17] and pendant drop [18] methods. The most commonly used techniques for measuring IFT were summarized by Drelich et al. [19]. Pendant drop method is used widely to evaluate the interfacial interaction [20]. It has the advantages of requiring very limited samples, and continuous and quick study of interfacial behavior [21,22].

More recently, after several methods such as the shape factor method and the regression method, ADSA technique has been developed numerically by Neumann and collaborators to measure the IFT from the shape of the fluid–liquid interface with high accuracy without using any of the previously generated tables [23,24]. In this study, the widely used method to date called ADSA-P (profile) was utilized, principles of which can be found elsewhere [25,26].

2.2. Effect of brine composition

Different trends have been reported for the effect of salt on interfacial tension. Several authors have observed an increase in IFT with salt addition in systems consisting of pure hydrocarbons, such as Ikeda et al., Cai et al., Badakshan and Bakes, and Aveyard and Saleem studies [27–30]. The latter authors reported that the IFT increases linearly as the molality of the electrolyte of different kinds of salt increases except KI, which shows a decreasing trend, in the dodecane-water system [30]. In contrast, Alotaibi and Nasr-El-Din's [31] results on N-dodecane indicated that low salinity does not always reduce the IFT since as it reaches the equilibrium after 5 min, the IFT of the 5 wt% NaCl solution drops compared to the other two systems (2 and 10 wt%). The reasons behind this phenomenon remained unknown at the time. Serrano-Saldaña et al. [32] observed fluctuated IFT values without presenting an explanation about this unexpected oscillation since oil/brine IFT normally increases with increasing the aqueous phase ionic strength. Cai et al. [28] claimed that the presence of salt in the aqueous phase increases the interfacial tension; however, this increase is considered to be independent of the kind of salt.

It is worth to mention here when an ionic surfactant is present in solution, increasing the salinity reduces the IFT [33,34]. Several mechanisms have been proposed for this behavior. Distribution of surfactants between oil and aqueous phase can be altered in presence of salts [35]. The increase in salt concentration and accordingly the ionic strength can also enhance the adsorption of surfactants and their diffusion to the interface [36,37], and increase the activity coefficient of the surfactant in the aqueous phase which decreases the interfacial tension [38,39].

Crude oil/brine interfacial properties are complex functions of widely various factors, such as temperature, pressure, salinity, TAN, and the amount of dissolved gases and asphaltenes [40] which makes it more difficult to deal with them compared to the pure systems [41–44]. Salts can have a significant effect on crude oil/water IFT, depending on the type and amount of surface active material present in the system.

Vijapurapu and Rao [45] investigated the effect of both synthetic and reservoir brine dilution on the IFT of dead Yates crude oil. IFT values decreased as increasing the dilution to 50% volume of brine mixed with deionized water (DIW), and then any further dilution beyond that increased the IFT significantly. A critical brine concentration was found to exist that lowered the IFT to a minimum value. In another study, Xu et al. [46] studied the effect of the brine composition on IFT by changing the salinity and salt composition using the live oil as the oil phase. The brine dilution did not influence dynamic IFT behavior, but it increased the IFT as compared to the original synthetic reservoir brine used in the system. Okasha and Alshiwaish [22] used dead as well as live crude oils and synthetic formation brine with three TDS values to measure the IFTs between the fluids and concluded that more research investigations are required to understand the mechanism of using low salinity brine to improve oil recovery. Their results show a decreasing trend in IFT with further dilution of high salinity brine with distilled water at fixed temperature.

Very recently, heavy crude oil with its polar components was studied by Bai et al. [37], who concluded that NaCl concentration had no considerable effect on the IFT reasoning that most of the interfacial active substance might be oil-soluble which minimizes the effect of salt as a result. Isaacs and Smolek [47] measured the IFT of Athabasca bitumen versus an aqueous phase and observed that an increase in salinity of the aqueous phase is accompanied by a decrease in IFT. The high density of the heavy crude oil being close to that of water, having difficulty in measuring its IFT against the aqueous phase, and heavy oil complexity in structure and behavior squeezed the number of the tests.

2.3. Effect of temperature and pressure

In general, oil/water IFT decreases with increasing temperature and increases with the increase in pressure for hydrocarbon/aqueous systems. Several authors have reported this kind of behavior [27–29,35,48–52]. However, the effect of pressure was found to be less than that of temperature [28,49,53]. On the other hand, opposite to what is expected, some authors have reported a decreasing trend in IFT with increasing pressure [54] and an increasing trend in IFT with increasing temperature [55]. A fluctuated behavior of IFT with pressure was also stated by Alotaibi and Nasr-El-Din [31]. They worked on N-dodecane and reported that increasing the temperature reduces the IFT linearly and that IFT normally increases with pressure, but with some fluctuation in results for 5 and 10 wt% NaCl solutions.

Despite the typical explained trend, contrasting behaviors were reported by many authors for crude oil/brine systems. IFT dependency on temperature was highly influenced by oil composition in Akstinat's [56] study which shows a decrease in IFT with increasing temperature in crude oils with a high naphthenic content and no considerable change in IFT in aromatic and paraffinic crudes. Increasing of IFT with increasing pressure at constant temperature was also observed by Hjelmeland and Larrondo [57]. Xu [20] investigated the pressure and temperature effects on formation brine/live oil system in a temperature range from 296.5 to 331 K and pressures up to 20.7 MPa. IFT increased linearly as pressure increased, and decreased when the temperature was changed at 20.7 MPa. A decrease in IFT of bitumen with temperature was reported by Drelich and Miller [58] and Isaacs and Smolek [47]. In Okasha's [22] experimental work, there is a little increase in IFT with pressure at constant temperature (up to 2 mN/m) and a