The effect of pressure on the phase behavior of surfactant systems: An experimental study

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HIGHLIGHTS

► We investigated the pressure effect on phase behavior of surfactant systems.
► Different water–oil ratios are investigated, while constant salinity and SAR.
► Formation of microemulsion phase is dependent on the pressure.
► It is observed that combined increase in pressure and temperature creates more pronounced influence on the phase behavior.

GRAPHICAL ABSTRACT
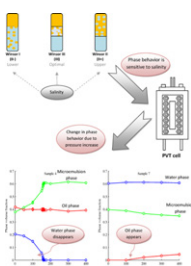
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ABSTRACT

Enhanced oil recovery is employed in many mature oil reservoirs to maintain or increase the reservoir recovery factor. In this context, surfactant flooding has recently gained interest again. Surfactant flooding is the injection of surfactants (and co-surfactants) into the reservoir, in order to create microemulsions at the interface between crude oil and water, thus obtaining very low interfacial tension, which consequently helps mobilize the trapped oil.

In this work a surfactant system, which has been thoroughly described at atmospheric pressure, is examined at elevated pressure. The effect of temperature is also explored. It was found that the phase behavior in the system water/sodium dodecyl sulfate (SDS)/1-butanol/heptane/sodium chloride was significantly changed by an increase in pressure. When an increase in pressure is combined with an increased temperature the phase behavior of the system is influenced to an even greater extent. It was concluded that at certain compositions of the surfactant system (near to the phase boundary found at atmospheric pressure) the increase in pressure changed the phase behavior (for example causing the system to move from two phases to three or vice versa). The sensitivity of the surfactant system depends very much on the overall composition as well as the magnitude of the pressure and temperature change.

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1. Introduction

Around half of the world's crude oil reserves remain trapped in reservoirs after conventional recovery methods have been applied. Enhanced oil recovery (EOR) is therefore increasingly applied in order to increase the reservoir recovery factor. In the EOR technique known as surfactant (or chemical) flooding, the phase behavior properties inside the reservoir can be advantageously manipulated by injecting surfactants (and usually co-surfactants) into the reservoir. The phase behavior in these surfactant systems is the decisive factor determining the success of a chemical flood [1]. However, there are at present no equations of state that can adequately describe the phase behavior of such complex systems. It is therefore essential that the phase behavior is experimentally determined in

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order to design a successful recovery process. In the design of the surfactant system the phase behavior should account for reservoir conditions (e.g. high pressure and high temperature), as it is crucial for this technique that the oil/surfactant/water system creates microemulsions during flooding. Formation of the microemulsion phase lowers the interfacial tension (IFT) between oil and water [2]. Ultra low IFT is further employed to mobilize trapped oil. It is well established that surfactant systems are sensitive to temperature and salinity [3], and widely accepted that detailed knowledge regarding the phase behavior of the oil/surfactant/water system is necessary to design an efficient surfactant flood.

Studies of the design of surfactants applicable for EOR have been carried out in several research groups. Anionic surfactants are those most commonly used for many applications (detergents, foaming agents, wetting agents, etc.) and are therefore potential EOR candidates—especially due to their low cost. Levitt et al. [4] and Flaaten et al. [5] report that branched alcohol propoxylate sulfate and internal olefin sulfonates are promising candidates with respect to both oil recovery and surfactant retention in the cores, where both studies show high oil recovery and low surfactant adsorption. Wu et al. [6] show that the average alkyl chain length and the number of propoxylate groups may influence optimal salinity, IFT and adsorption.

The phase behavior of surfactant systems has been studied both experimentally [e.g. 7,12–14] and theoretically [e.g. 8–16] in several projects and it varies whether the temperature and pressure dependency is included and considered as influencing parameters. Among the theoretical attempts to develop an approach to predict the influence from pressure accurately there are so far no true success regarding predictions of the phase behavior and as the understanding of the exact mechanisms, which is caused by high pressures, is poor this task is an ongoing challenge in the oil recovery field. Surfactant systems used for EOR will necessarily be at high (reservoir) pressures and improved understanding of the effect of high pressure will be beneficial in order to design optimized oil recovery processes.

The experiments in this study have been carried out in a high pressure DBR JEFRI PVT cell with the primary aim of ascertaining the influence of pressure on the phase behavior of a surfactant system and further to obtain an improved understanding of the influencing mechanisms. The model surfactant system water/sodium chloride (NaCl)/sodium dodecyl sulfate (SDS)/1-butanol/heptane was chosen. In the work by van Nieuwkoop and Snoei [7] this system has been operated and investigated thoroughly at ambient temperature and pressure. van Nieuwkoop and Snoei [7] observed that the three-phase region depends strongly on the overall composition parameters, such as salinity, water oil ratio (WOR), surfactant alcohol ratio (SAR) and total surfactant concentration. Sassen [12] has also studied this surfactant system as well as the subsystems influenced by pressure. Influence from pressure showed considerable influence on the phase behavior, where the surfactant system is studied at constant SAR and WOR, with both constant and varying salinity. In this work the starting point is from the results from van Nieuwkoop and Snoei [7] and in contrast to or a continuation of Sassen et al. [12] the surfactant system is studied with varying WOR and kept at constant SAR and constant salinity throughout all experiments. Several investigations of the phase behavior of water + oil + surfactant + alcohol systems are carried out at atmospheric pressure [9,10], and there is no consensus on the exact significance of the influence from pressure on such systems or how pressure possibly changes the phase behavior. Surfactant systems are in general classified according to the so-called Winsor type systems as shown in Fig. 1 and described by Nelson and Pope [11], where the desired ultra low IFT is achieved with the formation of a microemulsion phase, which is the Winsor III situation.
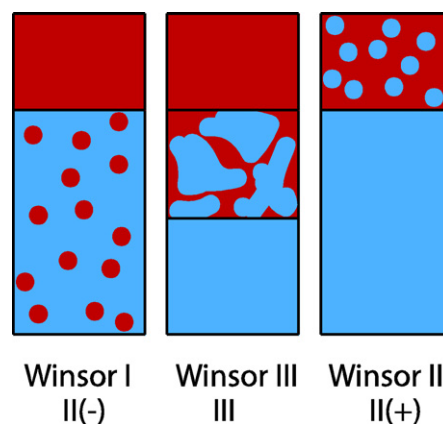

Fig. 1. Drawing of the Winsor type system [11] showing how surfactants are usually considered. From left to right is: Winsor I where oil/water microemulsions are present below the oil phase; Winsor III where the microemulsion phase is present as a third phase; and finally Winsor II water/oil emulsions are present above the water phase.

This phase behavior study is based on the diverse opinions from the literature as to whether elevated pressure has a significant effect on the multiphase region. Initially the purpose of the phase behavior study was to establish if pressure induces a change in the phase behavior of the system. Subsequently the model system was tested with different overall compositions at several different temperatures and pressures.

2. Experimental and equipment

This experimental study consists mainly of a thorough investigation of phase equilibrium study in the surfactant system mentioned, specifically the number of phases present and the volumes of the phases.

2.1. Chemicals

The system of pure heptane (Sigma–Aldrich), sodium dodecyl sulfate (Fluka, >99%), 1-butanol (Sigma–Aldrich), distilled water (from tap) and sodium chloride (Fluka, >99.5%) was used in the experimental work. All chemicals were used as purchased without any further purification. This system is used as a model system where several different compositions were examined. As the system is already described at room temperature and atmospheric pressure by van Nieuwkoop and Snoei [7] a good reference point is established in order to ascertain the effect of temperature and pressure.

2.2. Preparation of the starting composition of the samples

All chemicals were weighed on an analytical balance and transferred into a flask and stirred well together until SDS and NaCl were dissolved in the water/1-butanol/oil solution. To perform accurate phase volume measurements it was found that a total volume of 50–100 ml is necessary for each sample. Therefore all starting composition of the samples was prepared with a starting volume of 60–80 ml. The overall component weight fractions of the different surfactant systems are shown in Tables 1–3. The surfactant alcohol ratio (SAR) is held constant in all experiments at 0.5; similarly the overall salinity is kept constant at 6.56%. The water oil ratio (WOR) is varied from experiment to experiment.