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Full Length Article

Phase behaviour and characterization of microemulsion stabilized by a novel synthesized surfactant: Implications for enhanced oil recovery

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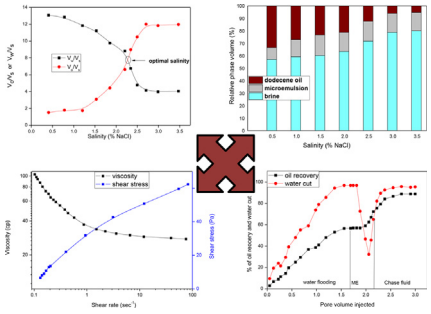
GRAPHICAL ABSTRACT



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ABSTRACT

The phase behavior of microemulsion systems comprised of methyl ester sulfonate (MES) as surfactant, propan-1-ol as cosurfactant, brine and alkane oils with varying chain lengths were studied for application in enhanced oil recovery. The aggregation and adsorption behavior of Jatropha oil-derived anionic surfactant were studied to investigate its favourability for use in microemulsion systems. Oil and water solubilisation parameters were determined in order to identify the optimal salinity values. The relative phase volumes were also studied as a salinity scan of microemulsion systems. The interfacial tension values between microemulsion and alkane systems were found to be much lower than that of surfactant and alkane systems. The prepared microemulsions were characterized by dynamic light scattering analysis and the particle sizes have been obtained in the range of 5–80 nm. Rheological studies revealed that the microemulsions exhibited non-Newtonian behaviour with favourably high viscosity values. Sandpack flooding using microemulsion systems was conducted at laboratory scale to predict the performance of microemulsion in oil recovery. It was found that the injected microemulsion formulations can achieve about 30% oil recovery close over conventional secondary water-flooding.

1. Introduction

The declining trend of oil production in oil industries poses significant concern as the demand for oil is increasing day by day. In order to meet current needs, enhanced oil recovery (EOR) techniques are being developed for recovering the residual trapped oil left in the reservoir. Surfactant flooding is one of the most favourable EOR methods in which interfacial tension (IFT) reduction at the oil-microemulsion interfaces takes place, displacing the trapped oil in the reservoir due to capillary effect [1–4]. The formation of microemulsion during

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surfactant flooding is a crucial stage in EOR. Use of surfactants in large amounts during the surfactant flooding process is often very expensive. Therefore, the cost effective microemulsion formulation is introduced into the reservoir which employs the use of optimum compositions of surfactant, cosurfactant, water and oil to achieve favourable physicochemical properties. This results in reduction of the overall cost of EOR process [5,6]. Microemulsion is one of the most important chemical flooding agents and an efficient tool for oil recovery due to its high level of oil extraction efficiency [7–9] and ability to solubilize organic and inorganic compounds present in the reservoir. However, microemulsion is isotropic, translucent or transparent, and comprises a thermodynamically stable dispersion of surfactant, cosurfactant, water or brine, and oil [10,11]. In microemulsion systems, a variety of phases can exist in equilibrium with one another. A microemulsion is basically characterized by analysing the phase behaviour of the system comprised of surfactant, co-surfactant, oil, and brine. The phase behaviour of microemulsion can alter from Winsor type I to Winsor type II through Winsor type III by adjusting the salinity at the same pressure and temperature [12]. Three phase microemulsion (Winsor III) systems offer ultralow IFT ($10^{-2}-10^{-4}$ mN/m). In this system, the microemulsion can be characterized by the presence of three phases. The middle phase consists of surfactant and equal amount of oil and brine that can be changed with salinity. The oil/water solubilization parameters can be defined as the volume of oil/water dissolved in microemulsion divided by the volume of surfactant present in microemulsion (V_o/V_s or V_w/V_s). Both of these parameters are very important design factors for economical application of microemulsion flooding process. The change in phase transition of microemulsion system is greatly influenced by several factors such as salinity, nature of oil, temperature, and water–oil ratio (WOR) [13,14]. Generally, the phase behaviour changes with variation of salt concentration. The surfactant solubility increases in oil phase with increase in salinity of aqueous phase. The oil solubilization power of anionic surfactant-stabilized microemulsion system increases significantly with increasing salinity. The microemulsion phase consists of oil droplets dispersed in aqueous medium (continuous phase). The surfactant and co-surfactant molecules generally form a monolayer of micro-interfaces between the oil and aqueous phases, aiding in improved surfactant solubilizing ability in microemulsion phase [15,16]. This causes variations in surfactant and co-surfactant (propan-1-ol) interactions in which partitioning effect of co-surfactant at interfaces dominate, and subsequently the adsorption of surfactant molecules at the interface between dispersed oil and surrounding aqueous phases is enhanced, allowing greater interaction between the oil and surfactant/co-surfactant molecules in microemulsion systems. The additional emulsifier molecules adsorb more easily onto the interface between microemulsion and excess oil phase. Earlier studies by Kunieda et al. [17]; Kunieda and Aoki [18]; and Ghorbaizadeh and Rostami [19] showed that salinity plays an important role in influencing surfactant solubility in oil phase. At low salinity, poor partitioning of surfactant/co-surfactant molecules onto the dispersed oil droplets occur and lesser oil is solubilized in the microemulsion phase. Increasing salt concentrations improves interactions between the oil droplets and surrounding emulsifier (surfactant/co-surfactant) molecules in the microemulsion phase till optimal salinity value is reached. When solubilisation parameters of oil and water are equal in a microemulsion system, corresponding salt concentration is called optimal salinity. Identification of optimal salinity is important due to its unique properties such as ultra-low IFT at the oil-microemulsion interface, thermodynamic stability and the ability to effectively solubilize both oil and water [8,20]. Therefore, microemulsions with optimal salinities are highly desirable for higher recovery.

Several researchers have already studied the microemulsion phase behaviour for its application in EOR process Addition of surfactant as well as co-surfactant is essential for achieving the favourable microemulsion systems in the presence of anionic surfactants to achieve improved solubilization and interfacial properties [21,22]. Abe and his co-workers investigated the physiochemical properties and phase behaviour of mixed system of sodium alkylsulfate and alkyltrimethylammonium chloride in the presence of alcohol as cosurfactant [21,22]. Furthermore, studies on the hydrodynamic diameter and interfacial tension values play a significant role in the optimization of microemulsion systems with varying alkane carbon number (ACN) of the oil component [22]. Furthermore, variations in alkyl length of the oil phase influence solubilization properties, depending on the nature and composition of the emulsifying agents such as surfactants and/or co-surfactant. Studies on the phase behaviour of oil/surfactant/co-surfactant/aqueous microemulsions for application in EOR revealed that microemulsion flooding process is a localized miscible process initially (until slug breakdown) and, thereafter, an immiscible process [22,23]. Selection of optimized slug formulation as well as identifying mechanisms of oil recovery such as IFT reduction and/or adsorption behavior is pivotal in order to achieve effective oil recovery in flooding experiments. By changing salinity, the volume of microemulsion phase changes due to variation of solubility of oil and water phase resulting in IFT reduction. From the higher oil recovery point of view, Winsor type-III system is most desirable for ultralow IFT, in which the upper layer contains oleic phase, the middle phase consists of oil, surfactant, co-surfactant mixture and the lower phase contains brine solution. In recent years, microemulsion flooding has become immensely important in the petroleum industry for EOR applications [24–26]. Currently, attention is focussed on the synthesis of surfactant from natural resources as well as the development of microemulsion for their application in chemical EOR. Similarly, Santanna et al. [9] synthesized an anionic surfactant from fatty acid-containing vegetable oil and formulated the microemulsion system for its application in EOR. Generally, alkyl ester sulfonates considered for application in EOR methods are expensive and the raw materials for synthesis are non-renewable petroleum derived products [27,28]. Alkyl benzene sulfonates also suffer from same drawbacks in application for EOR with additional disadvantages of biodegradability [29,30]. The current work on synthesis of methyl ester sulfonate (MES) from renewable source of Jatropha oil aims at mitigating the problems of present scenario of available surfactants. Therefore, the synthesis of MES and comprehensive study on prepared microemulsion systems would be able to draw attentions of researchers in new generation surfactants for EOR.

The present study attempts to investigate the phase behaviours and physicochemical properties of microemulsion systems of synthesized MES as anionic surfactant, propan-1-ol as co-surfactant, different alkanes with different values of equivalent alkane carbon number (EACN), and brine for the purpose of enhanced oil recovery. The solubilisation capacity of microemulsion system, solubilisation parameters and the relative phase volumes were measured by titration method, followed by visual observation. Pseudoternary phase diagrams were drawn for identification of microemulsion regions. Particle size distribution was analysed by dynamic light scattering (DLS) experiment. As the viscosity of injected fluid in oil recovery is one of the important factors, the rheological properties of prepared microemulsion were also analysed. Sandpack flooding experiments were also conducted with microemulsion slugs of desired formulations to determine the additional oil recovery.

2. Experimental

2.1. Materials required

MES from Jatropha oil has been used in our previous studies [31–33]. The Jatropha oil was obtained from the local market in India. It was initially purified by sedimentation process, followed by boiling in water [34]. Sedimentation of Jatropha oil was observed for a period of about 8–10 days to allow the impurities to settle at the bottom. Afterwards, the purification process was quickened by boiling the oil with water until the aqueous phase evaporated completely. The fatty acid