



Contents lists available at ScienceDirect

Colloids and Surfaces A: Physicochemical and Engineering Aspects

journal homepage: www.elsevier.com/locate/colsurfa

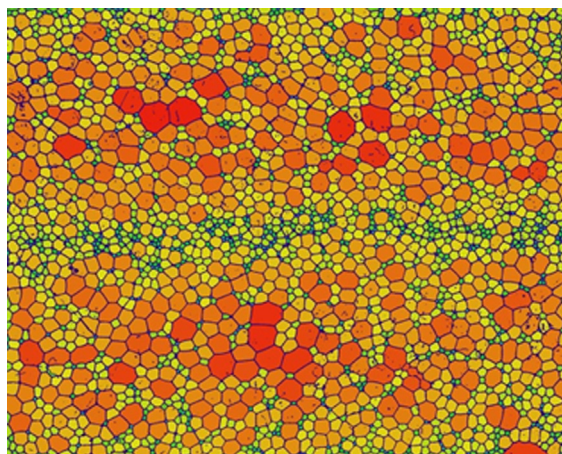
Foam stability in the presence and absence of hydrocarbons: From bubble- to bulk-scale

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HIGHLIGHTS

- Foam stability was investigated at both bulk- and bubble-scale.
- Effects of type of oil and surfactant on foam stability was investigated.
- Our results illustrated less stable foam in the presence of oil.
- Adverse impact on foam stability was reduced as oil viscosity and density increased.
- Presence of oil increases coarsening rate of foams deduced from the bubble-scale visualization.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:

Received 15 May 2015

Received in revised form 9 June 2015

Accepted 10 June 2015

Available online 15 June 2015

Keywords:

Foam stability

Foam-oil interaction

Surfactant

Bubble-scale visualization

Oil effects on

foam stability

ABSTRACT

One of the pioneering applications of foam is in enhanced oil recovery (EOR). A major stumbling-block to the success of foam application in EOR is the adverse influence of oil on foam stability. The objectives of the present work were to evaluate the effects of various surfactants and hydrocarbons with well-defined properties on foam stability. To do so, we have conducted a comprehensive series of experiments at bulk- and bubble-scale to investigate the foam stability of four surfactants in the absence and presence of three isoparaffins distinguished by their carbon chain length, density and viscosity. For the bulk foam stability experiments, foam was generated by sparging pure air into surfactant solution in a vertical cylindrical column. An automated camera was used to record the gradual decay of foam as a function of time. The results showed the significant impact of the type of the surfactant on foam stability. Besides, our results illustrated less stable foam in the presence of oil with less adverse impact on foam stability as oil viscosity and density increased. The limitation of the method used in the present study to quantify foam stability, i.e., measuring the decay of foam height over a certain period of time, which is a commonly used method in literature, is discussed here and an alternative approach is proposed to investigate foam stability at bubble-scale to supplement and improve understanding of the physical phenomena controlling foam stability.

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<http://dx.doi.org/10.1016/j.colsurfa.2015.06.023>

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1. Introduction

It is common in petroleum exploitation to inject water into reservoirs to drive out reservoir fluids as well as to maintain the reservoir pressure as the natural pressure of the reservoir declines over the course of production. Typically, about 65% of hydrocarbons remain unproduced after natural drive and water flooding [1,2]. This remaining oil is a target for enhanced oil recovery (EOR) methods such as gas injection and chemical EOR. Though gas recovery methods such as carbon dioxide and steam injection have shown potential to improve oil recovery, the major shortcomings of these EOR methods are their poor volumetric sweep efficiency (due to poor gas contact with oil) [3,4]. This occurs primarily because of reservoir heterogeneity and also the density and viscosity contrast between the injected gas and the reservoir fluids. Injected gas tends to flow preferentially through high permeability streaks (channelling) while viscosity and density differences result in viscous fingering and gravity override respectively [5–7].

Displacement by foam has proven to be a potential remedy to these complications, improving the efficiency of oil production [8–10]. Foam can be defined as a dispersion of gas in a liquid such that the liquid phase is continuous with some of the gas trapped in thin liquid films called lamellae [11]. The suitability of foam for EOR is due to its ability to reduce gas relative permeability by trapping gas bubbles in porous media [12]. The presence of bubbles increases the gas effective viscosity, which provides stability in the displacement process [13–17]. Foam also improves sweep by reducing gas mobility in high permeability areas thereby allowing diverted gas to sweep hydrocarbons in low permeability areas [12]. It has also been suggested that the presence of some surfactants in foam reduces capillary forces through reduction of interfacial tension between the displacing and displaced fluid [18].

The stability of foams is crucial to effective oil displacement. Foam stability is controlled by many factors associated with the physiochemical properties of the surfactant solution such as surface tension, surface viscosity and elasticity amongst others (see [19] for comprehensive information about the factors affecting foam stability). Among these factors is a parameter of paramount importance known as the disjoining pressure Π . The disjoining pressure is essentially the total pressure difference between the gas phase and the liquid phase within a film and it is highly dependent on the film thickness [19]. As described by the DLVO theory [20,21], contributions to disjoining forces arise fundamentally from two main sources: repulsive positive electrostatic potentials and attractive negative van der Waals potentials. The attractive van der Waals component results from the dipole-induced-dipole interactions between molecules across the film. These forces dominate where surfactant is absent making disjoining pressure negative and hence lamellae short lived. Upon the introduction of surfactant, the surfactant molecules adsorb onto the gas liquid interface. Surfactant adsorption results in an electrical double-layer which is the source of the repulsive force that stabilizes the lamellae. As a result, one of the parameters amongst others that define the degree of stabilization is the ionic strength of the aqueous solution [9].

One of the major challenges to the success of foam in EOR is the adverse influence of oil on foam stability and also characterisation of the complex interaction between foam and oil [14,22]. Results from bulk foam experiments in the literature show an apparent contradiction of the effect of oil on foam stability. Some authors have argued that the presence of oil, especially lighter hydrocarbons, destroy or prevent the generation of foam [23–25]. Others, however, have shown that stable foams can be generated in the presence of oil if an appropriate foaming agent is selected [22,26,27]. It has also been demonstrated that foam can be gener-

ated effectively in the presence of heavy oil [28,29]. Indeed, there are other experiments that suggest that oil can improve the stability of foam. For example, Aveyard et al. [30] conducted a series of experiments to delineate the correlation between alkanes and the half-life of a single foam bubble. While their results confirmed that lighter chain hydrocarbons radically reduce the longevity of foams, they also observed that longer chain hydrocarbons increased foam stability. Furthermore, Koczo et al. [31] have shown that emulsified oil can enhance the longevity of foams if the pseudoemulsion film is stable.

The destabilizing effects of oil on foam are believed to be a result of direct surface interactions between oil and foam which are determined by various physiochemical properties [14]. It is widely accepted that these interactions are governed by three main mechanisms; entry of oil droplet into gas-liquid interface [32,33], spreading of oil on the gas-liquid interface [34], and formation of an unstable bridge across lamella [35]. As discussed in Schramm and Novosad [24] the thermodynamic feasibility of oil destroying foam can be determined by evaluating the entering coefficient (E), spreading coefficient (S) and bridging coefficient (B). The mathematical expressions for E , S and B are given by

$$E = \sigma_{wg} + \sigma_{ow} + \sigma_{og} \quad (1)$$

$$S = \sigma_{wg} + \sigma_{ow} + \sigma_{og} \quad (2)$$

$$B = \sigma_{wg}^2 + \sigma_{ow}^2 + \sigma_{og}^2 \quad (3)$$

where σ_{wg} is the surface tension between surfactant solution and the gas, σ_{ow} is the interfacial tension between oil and surfactant solution and σ_{og} is the surface tension between the oil and gas.

The first condition to be satisfied for oil to destroy foam is that the oil droplet must be able to invade the gas–water interface [30]. This condition is met when $E > 0$ [33]. It is worth noting that, entering is not possible until oil is present in the form of emulsified oil, i.e., droplets with the droplet sizes smaller than the thickness of the foam lamella [24]. Once oil droplet has entered the gas-liquid interface, it will spread on the surface of the film. This occurs when $S > 0$ [32]. The spreading of the oil droplet over the film interface forces liquid out of the film into the Plateau borders which causes the film to thin and eventually rupture. Also, it has been suggested that the spreading of oil alters the film interfacial rheology which could change the rate of film drainage [36]. Ewers and Sutherland [37] suggested that both the entry and spreading condition must be satisfied for oil droplet to act as antifoam. On the contrary, when $S < 0$ (no oil spreading), oil forms a lens at the interface between the gas and liquid and may eventually destroy foam film if it makes its way into the lamella surface (bridging mechanism where $B \geq 0$) [30,38]. In fact, Vikingstad et al. [39] conducted a systematic static bulk foam test to investigate the factors that affect foam stability. Their results showed that negative spreading coefficient is not prerequisite for stable foam formation.

Mannhardt et al. [26] found that the stability of foams is related to the stability of pseudoemulsion films. When the pseudoemulsion film formed between the oil droplet and gas phase is stable, oil spreading is suppressed. Oil will only spread or bridge gas-liquid interface when the pseudoemulsion film ruptures. Manlowe and Radke [40] observed this mechanism in their pore-scale investigation of foam-oil interaction. They likewise concluded that the stability of foams is dependent on the stability of pseudoemulsion films and they did not find any relationship between oil spreading and foam stability. Similarly Koczo et al. [31] found that the entering and spreading coefficient had no correlation with the stability of foam as the pseudoemulsion film must rupture before oil can enter or spread in the air–water interface. Hadjiiski et al. [41] demonstrated from their experimental study the role of this ‘entry barrier’ in the destruction of foam by oil. They developed a novel

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