The relation between the dynamic surface tension and the foaming behaviour in a sparger setup

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HIGHLIGHTS

- Foam created using a sparger is related to the dynamic surface tension.
- For large surface tension reduction rates all liquid is incorporated into the foam.
- The foam liquid content is determined by the bubble size through drainage.
- Faster surface tension reduction leads to smaller bubbles and wetter foams.

GRAPHICAL ABSTRACT
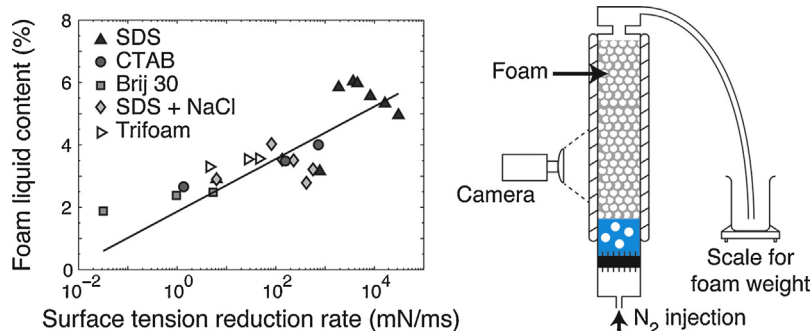
ABSTRACT

In this work, we relate the foam formation at a sparger with the dynamics of the surface tension, represented by the surface tension reduction rate ($R_{1/2}$). In our experimental setup, foam is formed at the bottom of a column, rises through the column and at the top of the column the total foam weight and the foam density are determined. The total foam weight is limited by the depletion of the surfactant, and increases with increasing surfactant concentration, and, therefore, with increasing $R_{1/2}$: at sufficiently large $R_{1/2}$, all the surfactants unload all the liquid from the column. The liquid content of the foam is determined by the foam drainage, which is strongly dependent on the bubble size, and, therefore, on the bubble generation at the sparger. A larger $R_{1/2}$ leads to smaller bubbles being formed and therefore to a larger liquid content of the foam. Even though the two foaming processes are quite different, we found that the correlation between the foam liquid content and $R_{1/2}$ in our sparger setup is similar to the correlation between the volume of foam and $R_{1/2}$ in a Ross–Miles test.

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1. Introduction

The understanding of the foaming behaviour of surfactants has relevance in many fields, such as gas and oil production, mineral flotation, food, cosmetics and personal hygiene. The current study is motivated by the application of surfactants to mitigate liquid loading in natural gas wells. When a gas well is liquid-loaded, the

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reservoir pressure has declined such that the velocity of the gas in the well tubing is no longer sufficient to lift the liquids associated with the gas to the surface [1]. The liquid accumulates at the bottom of the well, exerting a hydrostatic pressure on the reservoir, thereby severely limiting gas production. The injection of surfactants at the bottom of the well causes the liquid to foam, changing the properties of the liquid phase and decreasing the velocity of the gas that is required to lift the liquids to the surface [2].

To improve our understanding of the effects of these surfactants on the hydrodynamics of the flow in a gas well, we previously performed experiments in a large-scale flow loop (12 m in height, with internal diameters ranging from 34 mm to 80 mm) in which we evaluated the effects of the surfactants on vertical air–water pipe flow [3,4]. These experiments qualitatively explain how surfactants are able to deliquify gas wells. In these large-scale experiments, the hydrodynamics of the flow is very complex, and this complex flow behaviour leads to the entrainment of air into the liquid phase, thereby causing the formation of foam. The foam, in turn, affects the flow hydrodynamics, leading to a complex interaction between the flow morphology and the foam formation. The work presented in this paper is part of a systematic study in which we want to evaluate the effect of different parameters on the flow with surfactants in the large-scale flow loop.

To study the foaming behaviour separately from the complex hydrodynamics of the flow, we perform experiments in a small-scale facility. Here, we focus on the role of the (dynamic) surface tension: we study surfactants with different surface tension behaviour and quantify their foamability. In these small-scale experiments, we focus not only on the total amount of foam that is formed, but also on the liquid content of the foam. In the future, we aim at developing a mechanistic model on the effect of the surfactants on gas–liquid flows, for which results from small-scale experiments can be used as an input.

The behaviour of the foam in any setup depends on the physical–chemical properties of the surfactant solution and on the hydrodynamics of the foam formation (i.e. on the method through which the foam is generated). There are several common methods to generate foam, among which are the following: (1) the Ross–Miles test, which is a standard test in which a volume of surfactant solution is dropped on another volume of surfactant solution; the violent mixing of the two surfactant solutions and the gas in between them causes entrainment of bubbles into the liquid, which leads to the formation of foam. (2) A sparging setup, where gas bubbles are entrained into the liquid phase by blowing gas through a porous plate or through small capillaries. (3) Foam can be generated by shaking a test tube containing both gas and a surfactant solution, or (4) by stirring the surfactant solution vigorously, such that air is entrained into the liquid. (5) Foam can also be generated by nucleation of dissolved gas, which leads to bubble generation and foam, as occurs in beer or soft drinks.

In earlier research by Rosen and Hua [5], it was shown that the volume of foam formed in a Ross–Miles test scales with the dynamic surface tension: a faster reduction of the surface tension of newly created interfaces between the surfactant solution and the gas leads to the formation of a larger volume of foam. Unfortunately, in their work, the liquid content of the foam was not considered. In our work, we focus on the liquid content of the foam, and on a different hydrodynamics of the foam formation. In the Ross–Miles test, there exists a violent and complex mixing of the air and the surfactant solution. We consider a gentle and more regular method of foam formation, such that the effects of the surface tension and of the hydrodynamics can be easily separated. We consider a sparging test, used in the gas industry (see e.g. the work by Nguyen [6]), in which we measure the total mass of liquid carried upwards by the foam (m_f) and the liquid content of the foam (ϕ_l).

Even though our sparging test creates a completely different hydrodynamics from the Ross–Miles test, we still expect that the dynamic surface tension affects the foamability, since the dynamic surface tension affects the bubble generation at the sparger, thereby changing the average bubble diameter. The change in bubble diameter, subsequently, affects the drainage and therefore the liquid content of the foam. Indeed, we verify experimentally that the dynamics of the surface tension affect the results of the sparging test. Furthermore, we show that there exists a correlation between (i) the dynamic surface tension and m_f, and (ii) the dynamic surface tension and ϕ_l. We consider three different pure surfactants, and a commercial surfactant product that is commonly used in the gas industry.

In the remainder of the paper, in Section 2 the theory of the dynamic surface tension, the bubble formation and the liquid content of the foam is summarised. In Section 3, we consider previous work on the relation between the dynamic surface tension and the formation of foam. The experimental setup is explained in Section 4 and the results are presented in Section 5.

2. Theoretical background

A surfactant is a molecule with a hydrophilic head group and a hydrophobic tail. This structure causes the surfactants to preferentially adsorb at the interface between an apolar and a polar medium; in this work we form foam by sparging nitrogen gas into an aqueous surfactant solution, and the surfactants will absorb at the nitrogen–water interface. The apolar tails of the surfactants cause the surface tension, γ, to decrease. The equilibrium surface tension of surfactant solutions decreases with increasing surfactant concentration until the critical micelle concentration (cmc). When increasing the surfactant concentration above the cmc, the surfactants form agglomerates in the bulk solution, which ara called micelles. No additional surfactant molecules are adsorbed at the interface: the equilibrium surface tension no longer decreases with increasing surfactant concentration.

The decrease in the surface tension due to surfactants is not an instantaneous process: for example, when a new air-water interface is formed, the surface tension is initially $\gamma_{t=0} = 72.8$ mN/m, which is the surface tension for interfaces of pure water and nitrogen at room temperature and at atmospheric pressure. As surfactants diffuse to and adsorb at the interface, the surface tension decreases until the equilibrium surface tension is reached.

The dynamic surface tension (DST) has been studied extensively by Rosen et al. [5,7], who define the following empirical relation:

$$\gamma(t) = \gamma_m + \frac{\gamma_0 - \gamma_m}{1 + (t/t^*)^n} \tag{1}$$

In this relation, γ_0 is the surface tension of the solvent (in the current work 72.8 mN/m for air-water at 20 °C and 1 atm) and γ_m is the meso-equilibrium surface tension. Rosen and Xi [8] determine γ_m as the value of the surface tension when it decreases at a rate smaller than 1 mN/m per 30 s; it can often be approximated by the actual equilibrium surface tension. t^* is the time it takes, after the creation of the fresh surface, for the surface tension to become equal to $(\gamma_0 + \gamma_m)/2$; n determines the rate of reduction of the surface tension at $t = t^*$. These parameters can be determined from a fit of the measured data. In the literature, the surface tension reduction rate, defined as

$$R_{1/2} = \frac{\gamma_0 - \gamma_m}{2t^*} \tag{2}$$

is often used to characterise the dynamic surface tension; although, in the work by Rosen et al. [7], $\frac{d\gamma}{dt}|_{t^*}$ is used instead of $R_{1/2}$. A more detailed explanation of the dynamic surface tension can be found in [9].