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Effects of surface rheology and surface potential on foam stability

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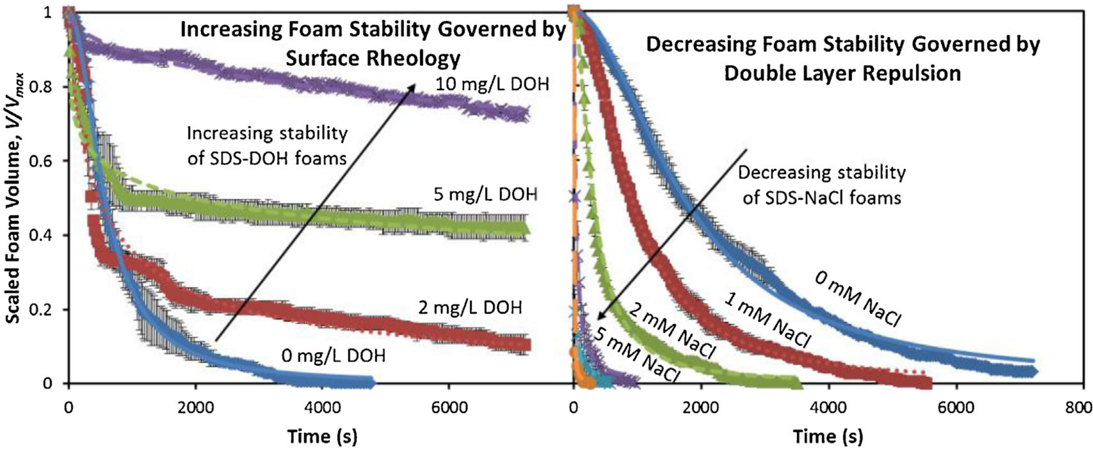
GRAPHICAL ABSTRACT



HIGHLIGHTS

- A model is proposed for foam collapse that was inspired by chemical kinetics.
- The stability of SDS–DOH foams is dominated by surface viscoelasticity, despite the decreased double-layer repulsion.
- The stability of SDS–NaCl foams is dominated by double-layer repulsion at the same surface concentration of SDS molecules.

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ABSTRACT

Here, we examine the collapse of standing aqueous foams stabilized by the anionic surfactant SDS, using DOH and sodium chloride (NaCl) respectively to produce different surface viscoelasticities and surface potentials in order to elucidate the roles of surface rheology and intermolecular forces in foam stability. Inspired from chemical kinetics, we proposed a model to quantify the foam collapse process and to compare the foam stability with two characteristic parameters: the foam half-life, τ, and the prefactor of foam collapse rate, n/τ. The presence of DOH in the SDS solutions can significantly increase the surface viscoelasticity and foam stability, despite the decreased surface potential caused by the displacement of SDS molecules by DOH molecules at the air–water interface. The correlation between surface viscoelasticity and foam stability is explained by the decrease in foam drainage and the increased liquid film stability. For SDS–NaCl mixtures with the same value of the mean ionic product (1 mM), an increased concentration of NaCl in the SDS solution reduces the surface potential and the Debye length because of the screening effect resulting from the binding of sodium counter ions to the sulfate head groups. The foam stability decreases because of the weakened repulsive interactions between the two interfaces of

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the liquid films, despite the presence of the same surface concentration of SDS molecules, as indicated by the same equilibrium surface tension. This paper highlights two different mechanisms that dominate foam stability.

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1. Introduction

Foam consists of a mixture of a large volume of gas with a much smaller amount of liquid. Despite its simple composition, the properties of foam are quite interesting in terms of its lightless and large specific area and because of the unique optical, electrical, thermal and mechanical characteristics [1–3]. The properties of foam allow them to be widely applied in our daily lives and in various industries, such as food, cosmetics, cleaning, surface treatment, building materials, reducing pollution and the extraction of natural resources (e.g., froth flotation) [1,3]. Because of its large surface area, a foam is thermodynamically unstable and irreversibly evolves and disappears with time [2]. The lifetime of a foam is known to depend on three interrelated mechanisms: the foam drainage caused by gravity, the coarsening caused by gas transfer between bubbles induced by capillary pressure differences, and the bubble coalescence caused by the rupture of liquid films between neighboring bubbles [1]. However, the mechanisms that determine foam collapse remain poorly understood. For example, although many research efforts have focused on the stability of liquid films, which constitute one of the elementary building blocks of foams (with the other being the Plateau borders) [4–6], the correlation between the stability of an isolated film and the stability of the entire foam layer is not fully understood [1,3]. The rupture of a single liquid film in foams has been shown to depend on previous rupture events; in other words, rupture occurs in correlated bursts [8–11]. Further, it has been correctly noted that [4], “In a real foam, the film are unlikely to burst at a single exerted pressure, but rather are likely to exhibit a distribution in the bursting probabilities.” However, little is known with regard to this distribution of bursting. Similarly, the dependence of foam collapse on the interfacial properties is also not well understood [1].

In this paper, we first review the theories regarding foam stability in terms of the interfacial properties and the surface forces in a single liquid film. Then, we propose a model inspired by chemical kinetics to describe the collapse of standing foams. Finally, we study the foam stability of SDS–DOH and SDS–NaCl foams to elucidate the effects of surface rheology and surface potential on foam stability.

2. Theory

2.1. Surface viscoelasticity and foam stability

The adsorption of surfactants on the air–water interface forms an adsorbed layer, which gives rise to interfacial viscoelasticity. Two types of interfacial rheology have been observed—interfacial shear rheology and dilational rheology—which characterize the response of the surface to shear stress and to extensional stress, respectively. In this study, we only focus on the effects of dilational viscoelasticity on foam stability [5]. The surface dilational modulus, ϵ, is defined as the ratio of the surface tension change, $d\gamma$, to the area change, dA/A, under dilational deformation:

$$\epsilon = \frac{d\sigma}{d\ln A} \tag{1}$$

In practice, the surface dilational modulus is expressed as two parts: (i) the surface dilational elasticity, ϵ', which measures the capacity of the air–water interface to resist a dilational deformation, and (ii) surface dilational viscosity, ϵ'', which measures the speed of the relaxation processes restoring the equilibrium after the disturbance. During a harmonic deformation, if the change in the surface area is sufficiently small, then the induced surface tension oscillations will be sinusoidal and the surface viscoelastic modulus, ϵ, can be expressed as a complex number [5]:

$$\epsilon = |\epsilon| e^{i\phi} = A_0 \frac{\Delta\sigma}{\Delta A}\cos\phi + iA_0 \frac{\Delta\sigma}{\Delta A}\sin\phi \tag{2}$$

where ϕ, $|\epsilon|$, A_0, $\Delta\sigma$ and ΔA are the phase shift between the surface tension and area oscillations, the surface dilational modulus, the mean area, and the amplitudes of the surface tension and the surface area variation, respectively (Fig. 1). It should be noted that the phase shift between the surface tension and area is caused by the diffusion of surfactant molecules from the bulk or air–water interface to the stretched area. We can calculate the surface dilational elasticity by $\epsilon' = A_0(\Delta\sigma/\Delta A)\cos\phi$ and the surface dilational viscosity by $\epsilon'' = (A_0/\omega)(\Delta\sigma/\Delta A)\sin\phi$, where ω is the angular frequency of oscillation.

The total harmonic distortion (THD), which estimates the deviation from linear behavior, is used as an estimation of measurement accuracy. It is defined as the ratio of the higher harmonics amplitude to the amplitude at the measured basic frequency [5]:

$$\mathrm{THD} = \frac{\sqrt{\sum_{k=2}^{n} a_k^2}}{a_1} \tag{3}$$

where a_1 is the amplitude value of the basic frequency and a_2, a_3, . . ., a_n are amplitudes of the higher harmonics. In this work, the THD values are below 10% in most cases.

Oscillatory area experiments were conducted to simulate liquid film thinning (Fig. 1). Assuming that the surface area of the film elements increases while its volume and the total amount of the surfactants remain constant and that the diffusion of surfactant molecules can be ignored, the surface concentration of surfactant molecules decreases during liquid film thinning. The reduction in the surface concentration induces a local increase in surface tension, which in turn resists the stretching of the liquid film and foam film drainage; consequently, the bubble coalescence rate decreases. High values of surface viscoelasticity can potentially lead to the suppression of marginal regeneration and a reduced rate of foam film drainage, which enhance foam stability.

2.2. Surface forces and foam stability

When two bubbles meet, surface forces act on the two interfaces separated by the thickness of the liquid. The disjoining pressure, Π_d, was defined to characterize the forces per unit area between these two interfaces. Fig. 2 illustrates the electrostatic, van der Waals, and steric contributions to the disjoining pressure in a film:

$$\Pi_\mathrm{d} = \Pi_\mathrm{dl} + \Pi_\mathrm{van} + \Pi_\mathrm{steric} \tag{4}$$

To enable the existence of a stable film, repulsive forces, such as the electrostatic force, must act between the interfaces. In this case, a positive disjoining pressure is induced in the film to counterbalance the attractive interactions that tend to rupture the liquid film.

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