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Historical perspective

A critical review of the growth, drainage and collapse of foams

Jianlong Wang [a], Anh V. Nguyen [a,*], Saeed Farrokhpay [b]

[a] School of Chemical Engineering, University of Queensland, Brisbane, QLD 4072, Australia
[b] Georessources, University of Lorraine, 2 rue du Doyen Marcel Roubault 54518 VANDOEUVRE LES NANCY CEDEX, France

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ABSTRACT

This review focuses on the current knowledge regarding (i) the mechanisms governing foamability and foam stability, and (ii) models for the foam column kinetics. Although different length scales of foam structure, such as air–water interface and liquid film, have been studied to elucidate the mechanisms that control the foamability and foam stability, many questions remain unanswered. It is due to the collective effects of different mechanisms involved and the complicated structures of foam sub-structures such as foam films, Plateau borders and nodes, and foam networks like soft porous materials. The current knowledge of the effects of solid particles on liquid film stability and foam drainage is also discussed to highlight gaps in our present level of understanding foam systems with solid particles. We also critically review and summarize the models that describe macroscopic foam behaviors, such as equilibrium foam height, foam growth and collapse, within the context of the mechanisms involved.

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* Corresponding author.
E-mail address: anh.nguyen@eng.uq.edu.au (A.V. Nguyen).

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1. Introduction

Foams are highly concentrated dispersions of gas (dispersed phase) in a liquid (continuous phase) [1]. Due to their lightness and large specific surface areas, foams are widely applied in our daily lives and industry. Examples of applications in which foams are used [2] include food, cosmetics, cleaning, surface treatment, building materials, reducing pollution (e.g., wastewater treatment [3] and heavy metal removal [4] by foam fractionation) and extraction of nature resources, i.e., froth flotation.

When producing a column of foam, different mechanisms either to produce and stabilize the foam column, such as the formation of liquid films and foams or to destroy it, such as coarsening of foams and drainage and rupture of liquid film and foams, get involved [2]. The combined effects of these mechanisms determine the lifetime of a foam or foam stability. The foamability of a solution is a measure of its capacity to produce a foam. During the foam formation, the surface energy $E = \sigma A$ increases with the creation of gas–liquid interfaces with the surface tension, σ and interfacial area A. The increased surface energy means the foam formation is not a spontaneous process, and the input of energy is indispensable to generate a column of foam. Based on the different ways to put energy into the liquid phase to generate foam, foaming techniques are categorized into physical, chemical and biological foaming [5]. We only focus on the mechanical foaming (the rotor–stator mixer method in Section 2.1.1 and the bubbling method in Section 3) that belongs to the physical foaming techniques in this review for the sake of its common application. Surfactants must also be present in the solution to promote the production of foam. The addition of surfactants stabilizes the liquid film and foams by altering the static surface tension (Section 2.1.1), adsorption kinetics (Section 2.1.1), surface viscoelasticity (Section 2.1.2) and interactions between two interfaces of a liquid film (Section 2.2.1). On the contrary, antifoams prevent the formation of foam by destroying the liquid film (Section 2.2.2). Solid particles also play an important role in the film stability (Section 2.2.3) and foam drainage (Section 2.4). Foam drainage for the aqueous foams (Section 2.3) is also discussed due to its importance for the foam growth and collapse. Finally, the models for the foam growth and collapse are reviewed (Section 3).

2. Mechanisms governing foamability and foam stability

Foamability and foam stability are two main foam properties of surfactant solutions. Foamability is an overall capacity of surfactant solution to produce foams, whereas foam stability refers to the lifetime of a foam column. These two terms are interrelated. For example, the foamability of a transient foam is believed to depend on its stability. Although these two terms are commonly used in the literature, there are no simple universal physical parameters to quantify them. Foam height and foam lifetime have been applied to characterize foamability and foam stability [6–8]. However, these two criteria are not satisfactory because they are not only dependent on the chemical composition of foaming solutions but also on the method of foam generation. Moreover, a general theory to explain the mechanisms of foam formation and stability for all types of foam system does not exist [9–11] because the magnitude and mutual importance of the different types of effects can vary significantly, depending on the stage of foam life and the conditions of its existence [10]. Bearing in mind the complicated interplay of various mechanisms, this review focuses on the existing theories that describe the mechanisms governing the foamability and foam stability.

2.1. Effects of interfacial properties on foam properties

The adsorption of surfactant molecules on the air–water interface alters the interfacial properties, and the foam properties change accordingly.

2.1.1. Surface tension and foamability

If the external energy applied to generate the foam is constant, then the foam surface area is inversely proportional to the surface tension. Therefore, a lower surface tension will increase the foamability of a solution from the perspective of surface energy. The other factor that influences the foamability is the bubble breakup. Foam generation involves creation and deformation of gas–liquid interface. When the mechanical method applies to foam generation, bubbles deform due to the external forces (e.g., shear stress or pressure of turbulence) that are subjected to the bubble surface. If the deformation is significantly large, bubbles can be split into smaller ones, and foam generation is possible. The critical Weber number, which is a dimensionless ratio between the inertial force (causing the deformation) and the surface tension (restoring the bubble sphericity), has been used as the criterion of the bubble breakup [12–18]. The bubble breakup occurs if the external forces applied to the bubbles make the Weber number exceed its critical value, which is of the order of unity. A lower surface tension ends up a large Weber number, therefore, promotes the bubble breakup process.

Although the role of surface tension in the foamability has been recognized regarding surface energy and bubble breakup process, the equilibrium surface tension is not reached instantaneously, and the dynamics of adsorption of surfactant molecules must be considered when the adsorption time is longer than the time scale of foam generation [10]. The evolution of the surface tension value is controlled by two processes: (i) the diffusion of surfactant molecules to the surface and (ii) the adsorption of surfactant molecules on the interface, which must overcome an associated energy barrier. Either of these processes may become the rate-determining step. The average lifetime of the bubbles at the solution/air interface during foam generation has been recommended as a rational choice of an adsorption reference time [19].

Research efforts of using different designs have focused on the effect of dynamic surface tension on the foamability. For example, the relationship between foam formation and dynamic surface tension of non-ionic and anionic surfactants has been studied using a rotor test, in which air is introduced to the surfactant solutions by a special stirring device [19]. A good correlation between foam formation and dynamic surface tension values at $t = 100$ ms has been found (Fig. 1). The relationship between foam formation and dynamic surface tension has also been investigated using the Ross-Miles test [20–22]. Recently, the foam formation by using a sparger was also related to the dynamic surface tension [23]. Fig. 2 shows a good correlation of foam height with the surface tension reduction rate, which is defined as follows [24]:

$$R_{1/2} = \frac{\sigma_0 - \sigma_m}{2t^*} \tag{1}$$

where σ_0 is the surface tension of the solvent, σ_m is the quasi-equilibrium surface tension at which the decrease rate of the surface tension is smaller than 1 mN/m per 30 s, and t^* is the time when the surface tension is equal to $(\sigma_0 - \sigma_m)/2$. Although the correlation between foam height and surface tension reduction rate has been found, we note that the surface tension reduction rate in Eq. (1) [22,24] is only an empirical equation and lacks a fundamental basis.

2.1.2. Surface viscoelasticity and foam properties

A century ago the effect of surface tension gradients on foam and film stability was discovered and described by Gibbs and Marangoni [25]. In 1941, Levich developed a theory to relate surface tension gradient with surface dilational elasticity [26]. However, only until 1970 [27] a new methodology for measuring the dilational rheology via a harmonically oscillating bubble has paved the way for the first commercial instrument for routine experimental determination of the dilational surface elasticity [28], based on oscillating drops and bubbles. Various aspects of surface viscoelasticity have been reviewed [29–33] and a book devoted to surface viscoelasticity has been published recently [34].