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Short communication

# Analysis of creaming and formation of foam layer in aerated liquid

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ABSTRACT

A model for creaming and formation of a foam layer in an aerated system consisting of Newtonian liquid is proposed. The variation of air volume fraction in the dispersion layer is described by hindered creaming which is coupled to syneresis in the top foam layer that is described by flow of liquid through a network of Plateau borders due to gravitational and capillary forces. The present analysis accounts for the compressibility of foam layer by coupling creaming analysis with syneresis in the foam layer. The behavior of the system is described by three parameters: (a) characteristic time scale of creaming of an isolated bubble, (b) hydrodynamic interaction factor, and (c) capillary number, ratio of capillary and gravitational forces in the foam layer. System behavior is shown to be different for four different regions of initial air volume fractions for which the phase diagram and evolution of the profile of air volume fraction for batch dispersion are presented.



## 1. Introduction

Aerated products are very popular. Foaming has become one of the fastest growing processing operations for the development of new innovative products. Air is incorporated in the form of fine bubbles in order to render texture to these products. Air is incorporated into these products by a variety of different techniques such as fermentation, whipping, mixing, vacuum expansion, and gas injection. The incorporated bubbles are usually stabilized by proteins and other emulsifiers which, being surface active, adsorb onto the bubble surface and prevent coarsening due to coalescence by modifying the interparticle forces as well as by providing interfacial rheological properties. In liquid products, air incorporation results in an air–liquid dispersion in which the air bubbles cream (due to density difference) to the top to form a foam layer. The texture and shelf life of the foam layer depend on the amount of liquid retained by the foam which, in turn, is determined by syneresis. Excellent reviews on creation and characterization of aerated food products [1] and foam stability [2] can be found.

Extensive investigations have been carried out to describe sedimentation of particles in liquid medium. Kynch [3] developed a classic theory of sedimentation which was further amplified [4] to describe the particle movement by the method of characteristics. The earlier theory assumed monodispersed nondeformable particles which upon sedimentation formed an incompressible layer of close-packed particles. It has been shown [5] that the effect of interparticle forces in the sedimentation layer is equivalent to an osmotic pressure. The effects of polydispersity [6] and compressibility of sediment layer [7,8] have been considered. In the case of compressible sediment, the compressibility is described in terms of sediment structure and porosity. Monte Carlo simulation of creaming and flocculation of emulsion drops has been carried out to describe the concentration profile and fractal dimension of flocculated networks [9]. In the case of air–liquid dispersion, creaming of bubbles results in the formation of a compressible foam layer in which gas bubbles are distorted in the form of polyhedra because of their high volume fraction. Bubbles are separated by thin films. Three adjacent thin films intersect in a Plateau border and the continuous phase liquid is interconnected through a network of Plateau borders [10]. The Plateau border suction as a result of its radius of curvature leads to drainage of liquid from thin films to the neighboring Plateau border. This is counteracted by disjoining pressure caused by van der Waals, electrostatic, and steric interactions between two approaching faces of a draining film [11]. As the liquid in the Plateau border drains due to gravity through a Plateau border network [12], the top of the foam becomes drier with a smaller Plateau border cross-sectional area and hence smaller radius of curvature. With time, there develops a gradient of Plateau border suction in the foam as a result of gradient of liquid holdup. This gradient opposes gravity [13], thus retarding Plateau border drainage. Mechanistic models for foam drainage based on foam structure have been developed [13–19] and employed to describe the evolution of liquid holdup profile and foam collapse [13,17,18] . Models for Plateau border drainage of power law fluid have been proposed for actual Plateau border geometry for immobile [20] as well as mobile [21] gas–liquid interfaces. A liquid holdup profile in a standing foam was measured using magnetic

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resonance imaging [20,22–24] and compared with model predictions [20,21]. A population balance analysis has been proposed [18] to describe the evolution of bubble size distribution due to coalescence and interbubble gas diffusion. Rupture of thin films due to thermal and mechanical [25] perturbations has been analyzed using linear [26–30] and nonlinear [31–33] stability analysis and incorporated in the prediction of foam collapse [17].

In this paper, a model for creaming of air bubbles in a Newtonian liquid is proposed which accounts for the formation of foam layer. *The compressibility of foam layer is described in terms of syneresis of liquid through the interconnected network of Plateau borders.* Balance equations for the cream and foam layers are solved in order to obtain the phase diagram of the dispersion as a plot of height vs. time for different air volume fractions. The phase diagram is then employed to predict the evolution of profile of air volume fraction for initially uniformly distributed air liquid dispersions of different volume fractions.

## 2. Analysis of creaming of bubbles in air–liquid dispersion

Consider an air–liquid dispersion consisting of bubbles of the same size $a$ and distributed uniformly in a container of height $h$. Because of the density difference, air bubbles will cream. In the case of dispersion of sufficiently high volume fraction, the creaming velocity will be reduced by the hydrodynamic interaction between neighboring bubbles. The creaming velocity will depend on the density difference, bubble size, viscosity of the liquid, and air volume fraction. Since all bubbles cream at the same velocity, creaming will result in a sharp interface of clear liquid at the bottom and air–liquid dispersion in the rest of the container. Since the bubbles that reach the top accumulate (unless they break), a foam layer is formed at the top. With time, the height of this foam layer increases. This accumulation also leads to an increase in the air volume fraction with height. One can identify different regions, namely (i) a bottom clear liquid region, (ii) a region of same air volume fraction as the initial volume fraction, (iii) a transition region of increasing air volume fraction, and (iv) a foam layer where the air bubbles are closely packed and deformed (see Fig. 1). These regions are separated by clear demarcations. Conventional analysis of batch creaming (or settling) deals with *undeformable* solid particles and therefore predicts the formation of a top layer of close-packed spheres. *Here, we incorporate the deformation of spherical bubbles in the foam layer accounting for the structure of foam.* As the foam layer is formed, the liquid in the foam layer will continue to drain because of gravity and capillary forces. As the liquid drains, the bubbles will deform into polyhedra with their faces being separated by thin films. The drained liquid from the foam layer will travel through the other layers that lie below it. The analysis of creaming in the air–liquid dispersion is based on classical theory of sedimentation [3,34]. *Unlike the classical theory, however, the present analysis accounts for the compressibility of foam layer by coupling creaming analysis with syneresis in the foam layer.*

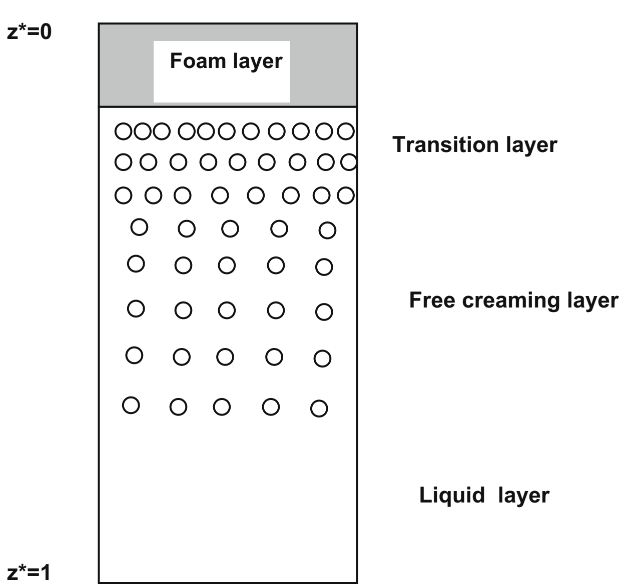


**Fig. 1.** Different regions in a standing air–liquid dispersion due to creaming.

## 3. Air–liquid dispersion

The balance equation for the dispersed phase in the bottom air–liquid dispersion layer I yields [34]:

$$\frac{\partial \phi^{\mathrm{I}}}{\partial t} - \frac{\partial}{\partial z}\phi^{\mathrm{I}}U(\phi) = \frac{D_0}{U_0}\frac{\partial}{\partial z}\left[U(\phi)\frac{d}{d\phi}[\phi^{\mathrm{I}}Z(\phi)]\frac{\partial \phi^{\mathrm{I}}}{\partial z}\right], \tag{1}$$

where $\phi^{\mathrm{I}}$ is the air volume fraction in the cream layer, $U(\phi)$ is the creaming velocity of a bubble in a dispersion of volume fraction $\phi$, $U_0$ is the free creaming velocity of an isolated air bubble in the liquid medium, $D_0 = kT/6\pi\mu a$ is the Stokes–Einstein diffusion coefficient and $Z(\phi)$ is the compressibility factor. Defining dimensionless quantities,

$$t^* = \frac{U_0 t}{h}, \quad z^* = \frac{z}{h}. \tag{2}$$

Eq. (1) can be recast as

$$\frac{\partial \phi^{\mathrm{I}}}{\partial t^*} - \frac{\partial}{\partial z^*}\phi^{\mathrm{I}}U^*(\phi) = \frac{1}{Pe}\frac{\partial}{\partial z^*}\left[U^*(\phi)\frac{d}{d\phi}[\phi Z(\phi)]\frac{\partial \phi^{\mathrm{I}}}{\partial z^*}\right], \tag{3}$$

where $U^*(\phi) = U(\phi)/U_0$ is the dimensionless creaming velocity or hydrodynamic interaction factor and the dimensionless Peclet number $Pe$ is given by

$$Pe = \frac{U_0 h}{D_0} \tag{4}$$

For a typical value of $a = 5 \times 10^{-4}$ m, $h = 5 \times 10^{-2}$ m, $\Delta\rho = 10^3$ kg/m$^3$, and $T = 298$ K, $Pe = 6.245 \times 10^{13}$. Consequently, $Pe \gg 1$ and the order of the differential equation that describes the dispersed phase fraction profile reduces to first order since the thermodynamic forces are negligible, i.e.,

$$\frac{\partial \phi^{\mathrm{I}}}{\partial t^*} = \frac{\partial}{\partial z^*}\phi^{\mathrm{I}}U^*(\phi) = \frac{\partial S^{\mathrm{I}}}{\partial z^*}, \tag{4a}$$

where the flux of bubbles $S^{\mathrm{I}} = \phi^{\mathrm{I}}U^*(\phi)$. Because of creaming of bubbles, the volume fraction of the bubbles increases from the bottom to top. Consequently, the flux of bubbles also changes with height. Eq. (4a) can be rewritten as

$$\frac{\partial \phi^{\mathrm{I}}}{\partial t^*} = \frac{\partial S^{\mathrm{I}}}{\partial \phi}\frac{\partial \phi^{\mathrm{I}}}{\partial z^*} = -V(\phi)\frac{\partial \phi^{\mathrm{I}}}{\partial z^*}, \tag{5}$$

where $V(\phi) = -\frac{\partial S^{\mathrm{I}}(\phi)}{\partial \phi}$ is the velocity of movement of a layer of volume fraction $\phi$. Eq. (5) can be rewritten in terms of a characteristic $\xi$ as:

$$\frac{d\phi^{\mathrm{I}}}{d\xi} = \frac{\partial \phi^{\mathrm{I}}}{\partial t^*} + V(\phi)\frac{\partial \phi^{\mathrm{I}}}{\partial z^*} = 0. \tag{6}$$

The characteristic $\xi$ is related to $t^*$ and $z^*$ via

$$\frac{\partial t^*}{\partial \xi} = 1; \ \frac{\partial z^*}{\partial \xi} = V(\phi). \tag{7}$$

Therefore, in the $z^*{-}t^*$ plane, the characteristic is given by a straight line of slope $V(\phi)$. From Eq. (6), it can be seen that the