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Quantifying liquid drainage in egg-white sucrose foams by resistivity measurements

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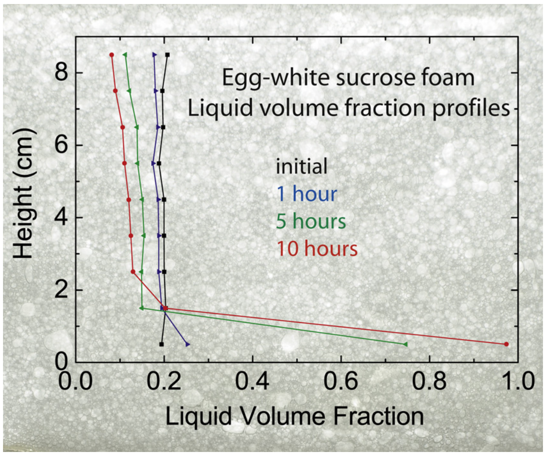
HIGHLIGHTS

- The drainage properties and stability of egg-white sucrose foams are quantified.
- A new high-resolution AC conductance meter enables very accurate resistance measurements.
- The resistance measurements have improved resolution as a function of foam height compared with previous data.
- High gas volume fraction foams made from egg-white sucrose mixtures are shown to be very stable.
- Little drainage is evident in these foams even after 200 min.

GRAPHICAL ABSTRACT



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ABSTRACT

Free drainage in egg-white foams with a variety of gas volume fractions was investigated by an electrical resistivity technique. Changes in resistivity at different heights in the foam were monitored as a function of time thus giving information on the local liquid volume fraction (or content) and therefore the rate of foam drainage. The wettest egg-white foam was the most unstable, with changes in liquid volume fraction observed within minutes of foam aging. Because bubble sizes are very small, a huge effect of capillary forces confers egg-white foams with a very good stability to drainage. The complex nature of the egg-white liquid (bulk and interfacial properties), the likely presence of denatured-aggregate complexes in the Plateau borders, and very small bubble sizes are key parameters for understanding the stability of egg-white foams that makes them excellent foaming materials for food science and culinary purposes.

1. Introduction

Bubbly liquids and foams elicit a great deal of scientific interest because of their unusual properties [1–3]. Bubbly liquids consist of unpacked dispersions of bubbles in liquid, while foams are highly packed structures of bubbles. In a foam, bubbles packed

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together form an interconnected structure, composed of films, Plateau borders and nodes. Because of this mechanical structure, foams can exhibit elastic, plastic or viscous behavior depending on the mechanical solicitation, contrary to bubbly liquids whose properties remain more liquid-like in character. The mechanical properties of foams are strongly linked to the bubble size distribution and the liquid volume fraction [4].

As well as being of scientific interest, bubbly liquids and foams are of substantial technological interest and value. For example, solid foams, created from solidification of liquid foams, are useful in a variety of mass-sensitive applications where their high ratios of modulus and strength relative to mass confer a number of performance advantages [5]. Liquid foams have a number of purposes in the petroleum industry [6], in fire-fighting technologies [7], and numerous foam fractionation applications are evident in the chemical processing industries [8,9]. Liquid foams are also of great interest in the cosmetic industry [7].

Bubbly liquids also prove their utility in industrial processes, particularly for mass transfer applications [10,11]. Their interesting nature is also exploited in biology, bubble clouds that enhance biomedical ultrasonic imaging techniques being one example [12,13], while the generation of bubble clouds by killer whales for corralling prey is an interesting example from nature [14]. Another biological application is in the kitchen and in commercial food production because aerated and foamed food products (e.g., wafers, meringues, angel food cakes, soufflés) are highly valued and popular products due to their capacity to create soft textures and appealing mouth feel [15–17].

Until solidification of the liquid matrix material, the structures of both foams and bubbly liquids are prone to significant changes over time [1,2,18–21]. These “aging” changes in aerated systems can be divided into two categories: aging by coarsening (disproportionation and coalescence) and aging induced by gravity.

Disproportionation and bubble coalescence are processes inducing an average bubble size growth with time. In foams both mechanisms occur, whereas in bubbly liquids disproportionation is the only mechanism. Disproportionation is driven by Laplace pressure differences that exist between bubbles of different sizes. The diffusion of gas from the smaller bubbles, where it is at a higher pressure, leads to a coarsening process where the median bubble size grows steadily over time [22,23]. Coalescence is the event where the liquid film separating adjacent bubbles in a foam thins so much that it catastrophically breaks down [19,24–26]. The rate of coalescence depends on bubble geometry and film drainage time, but also on an additional stochastic parameter, the probability of a rupture event per unit time and per unit surface area of the films [24–26].

Both foams and bubbly liquids undergo gravity-driven aging processes: creaming in the case of a bubbly liquid, drainage in the case of foam. In gravity-driven aging processes, the large density differences between the dispersed gas phase and the liquid matrix material causes bubbles to cream in bubbly liquids, except in very high viscosity matrices such as reactive polyurethane systems [27] and dough [28]. In foams, bubbles are locked in place by their neighbors [2] so that creaming does not occur. Instead, because of gravity, the liquid contained in the foam flows downward through the network of Plateau borders and nodes permeating the structure of the foam [19,21].

In foams the extent to which a particular aging mechanism dominates foam destabilization depends considerably on the foam's gas content. Indeed, the volume fraction of gas separates foams into two categories in terms of their rheological properties: wet foams and dry foams [1,2,19,21]. Wet foams are more prone to instability due to drainage, whereas in dry foams disproportionation is enhanced by the thin films separating the bubbles. Aging mechanisms very often impact each other; for instance, disproportionation can be accelerated by the effects of drainage [1,3,18,19].

Because changes in the structure of bubbly liquids and foams affect their end-use performance [16,17], or the way in which solidification occurs in the material [5,29], there is a need to understand aging mechanisms in order to control them. Egg-white sucrose foams are a classic food example to illustrate the challenges one faces in the kitchen and in industrial manufacturing facilities if one is to create a foam that has desirable end-use properties [15,30–33]. The challenge arises because the liquid foam is simultaneously undergoing drainage, disproportionation and coalescence, and these destabilization phenomena are enhanced as the temperature rises in the initial stages of baking (20–60 °C) [31]. Angel food cake made from such a foam is a good example, for if the cake batter is not optimally aerated, accelerated drainage due to lower liquid viscosity leads to cake failure [32]. Over-aeration accelerates the rate of disproportionation and coalescence, due to reduced separation between bubbles [1,2], again inducing cake failure. Therefore, it is important to understand instability mechanisms and quantitatively evaluate the aging process in foams used for cake making in order to advance and initiate new bakery formulations and cake-making technologies.

The objective of this paper is to study drainage-induced aging phenomena in egg-white foams of varying gas volume fraction, with a view to understanding aging mechanisms that affect the quality of the final product. The free drainage experimental design was based on a realistic angel food cake making process: the height of the experimental cell was approximately that of the pan height used for angel food cakes. To interpret mechanisms associated with the drainage process in egg-white foams, the specific properties of the egg-white foams were considered: small bubble size, nature of the proteins and their behavior in the foam network, the nature of the liquid-foam/air interfaces and the high interfacial viscosity. Analyzing the drainage behavior of the studied foam, we show that liquid flow in the foam network was very slow relative to small molecule surfactant foams typically used for foam drainage studies.

2. Experimental

2.1. Foam sample preparation and characterization

To make the base egg-white foams, a typical formulation was chosen that is suited for angel food cake [18,32,33], except that soft wheat flour, salt, and cream of tartar were omitted; the former to obviate changes in foam structure that would arise from flour addition, and the latter two, because as strong electrolytes, they would interfere with foam resistivity measurements. Accordingly, 83 g sucrose and 83 g of egg white were used for all experiments. Except for the highest gas volume fraction, where egg white was separated from fresh eggs, liquid egg whites (Innovatech, Winnipeg, MB) were used. Liquid egg whites were kept frozen at −20 °C until needed. Prior to each experiment, the liquid egg whites were defrosted at 4 °C for 12 h and then allowed to reach ambient temperature (22 °C). The liquid egg whites were then filtered through cheese cloth to remove particulates. Powdered sucrose of fine particle size (for ready dissolution) was bought in 1 kg bags (Rogers Sugar Ltd.).

A small scale domestic Kitchen Aid (Hobart Company, Model 4C, 200 W) variable-speed mixer with a stainless steel three-wire whip was used to create the foams. Initially, the sugar and egg whites were blended in a steel bowl at very low speed (speed 1) for 5 min to dissolve the sucrose. Afterwards, high speed mixing (speed 6) was used to occlude air into the mixture. Four high speed mixing times were chosen to obtain egg-white foams with gas volume fractions of 0.60, 0.65, 0.78 and 0.81. Gas volume fractions (ϕ) in the foams