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A population balance treatment of bubble size evolution in free draining foams

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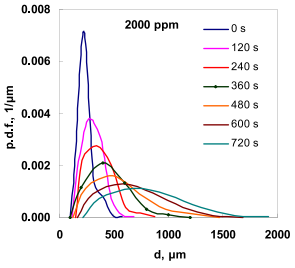
HIGHLIGHTS

- Experimental bubble size distribution evolution in a draining foam.
- The distributions follow a log-normal shape with evolving parameters.
- Inverse population balance problem for coalescence and/or ripening rates.

GRAPHICAL ABSTRACT

Evolving size distributions of bubbles in a foam undergoing simultaneous drainage, coalescence and ripening.



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ABSTRACT

Modeling foam drainage is an important step in understanding foam stability properties. There is a two way coupling between foam drainage dynamics and bubble size evolution. The bubble size evolution is determined in the general case by two processes: ripening and coalescence. The ripening problem modeling is relatively easy and it has been extensively studied. The coalescence problem is very complex and its modeling attempts are limited. The most sophisticated studies are based on the statistics of bubble films leading to the evolution of the average bubble size. Here an alternative approach to indirect modeling of the coalescence process is attempted. Experimental results of the evolution of bubble size distribution in free draining foams are registered. Then the so called inverse population balance approach is invoked to estimate the coalescence and ripening rates leading to the experimental bubble size evolution. Several surfactant concentrations are employed to yield foams of varying stability. It is shown that the experimental bubble size distributions can be adequately described in all cases by a log-normal distribution. This simplifies vastly the inverse problem solution since approximate methods can now be used for the solution of the population balance equation.

1. Introduction

The appearance of foams in many practical applications, e.g., in foods, detergents, cosmetics and mineral separations, motivated an extensive scientific study of their properties. Foams are structured gas/liquid fluids in which gas bubbles are separated by liquid layers that can be relatively thick (wet foams) or thin (dry foams). Foams are destabilized through various mechanisms. Drainage is a major foam destabilization mechanism referring to the flow of liquid relative to bubbles driven by gravity and capillary forces [1]. In addition, foams destabilize because bubble size increases with time. This is attributed to two mechanisms. The first one refers to diffusion of gas across films from small bubbles (high pressure) to large bubbles (low pressure) known as

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foam coarsening or disproportionation or Ostwald ripening. The term ripening will be used to describe this mechanism henceforth. The second one refers to destabilization of films between neighboring bubbles as they get thinner and become unstable and break; this is known as bubble coalescence. Bubble size distribution affects the capillary pressure and the cross section of flow channels (known as Plateau borders) so it affects the drainage rate [2].

There are several modeling attempts of the drainage process in literature having different degree of sophistication. Typically, bubble radius is considered as an input parameter for these models. An alternative approach is to simultaneously model drainage and coalescence processes. Direct modeling of the coalescence process is extremely cumbersome because it not only alters the topology of the two coalescing bubbles but also changes the topology of all adjacent bubbles [3]. In addition, the number of bubbles in a real foam is too large for a detailed treatment. Instead, a homogenization approach is followed. The foam is considered to have a homogeneous structure with its differential element to include many bubbles (a modeling approach very common in the study of porous media) [4]. In this respect, a dynamic model for the evolution of bubble size distribution is needed. Development of such a model has been presented in detail in [5,6]. The model is based on the thinning and rupture dynamics of the intrabubble films and it is based on an assumed initial distribution of the thickness of thin films. The approach predicts the evolution of the thickness distribution of the films through the appropriate population balance. Unfortunately, the film thickness distribution is not related to the bubble size distribution further to the relation between total film number and average bubble size. Unlike the coalescence case, the modeling approach of ripening is well-established. The model is typically use to extract parameters as the average film thickness from the experimental data. In those works the coalescence is avoided by using large amount of surfactant. The idea here is to use small quantities of surfactant to allow coalescence.

A different modeling formulation is used here in the sense of the so-called inverse population balance problem. The evolution of bubble size distribution is described by the coagulation-ripening population balance. The coagulation (coalescence) kernel function and the ripening parameter are estimated by matching modeled and experimental local bubble size evolution. Such a model can be used to describe the evolution of the local bubble size distribution in a distributed foam drainage model.

The structure of the present work is the following: At first, the experimental procedure of measuring bubble size distributions during foam drainage is described and the evolving distributions are presented. The equations used to fit the distributions and their handling is discussed next. Then the inverse population balance is formulated and it is reduced to a simpler one dealing only with average bubble volume and size distribution dispersivity. Finally, inversion procedures based on two different scenarios are attempted.

2. Experimental part

2.1. Foam preparation

Experiments are performed with deionized water and sodium dodecyl sulfate (SDS; Fluka) surfactant solution. Four concentrations of SDS (300, 600, 1000 and 2000 ppm) are employed which are below the reported CMC value at 30 °C (~2500 ppm [7]). SDS is known to produce foams unstable with respect to coalescence [8]. Study of the influence of below the CMC surfactant concentrations on foam stability and bubble sizes is very limited in literature. Specifically, the effect of different types (i.e. Dowfroth-250, Dowfroth-400 and SDS) and various concentrations of surfactants (below the CMC) on foam lifetime is studied in [9]. It is showed that foam stability is controlled not only by the liquid drainage process, which is a function of surface shear viscosity, μ_s, but also by the film rupture process which is a function of other interfacial properties (e.g. surface dilatational viscosity of adsorbed layers). Furthermore, they showed that the ability of surfactants to prevent bubble coalescence increases as surfactant concentration increases approaching CMC, resulting to smaller bubbles. Nevertheless a more quantitative treatment of the observed coalescence process has not been attempted in the past.

Table 1
Initial liquid volume fraction and average bubble size of the freshly-produced foam.

ppm	300	600	1000	2000
Initial volume fraction	0.145	0.131	0.128	0.116
Average bubble size (μm)	405	385	353	240

A small amount of NaCl (4×10^{-3} M corresponding to Debye screening length of 4.8 nm) is added to the deionized water to yield the ionic strength that is met in applications where foams are produced from fresh (mineral) water. This is such a small amount so as to avoid the fouling problems created by calcium and magnesium salts. This small concentration of salt does not affect interfacial properties. The concentrations of SDS used here are relatively small in order to permit measurable coalescence rates. In foam literature, much higher SDS concentrations are typically used in order to prevent coalescence and study alone the drainage or coarsening processes [10].

Foams are prepared by whipping air into 200 ml of the SDS solution using a stand mixer (POWER PLUS, Izzy) for 10 min. This intense production method, apart from being technologically more realistic than the bubbling method (e.g. in terms of polydispersity), allows also creating large volumes of initially uniform and homogeneous foam columns [11,12]. The initial liquid volume fraction and average bubble size of the freshly-produced foam are presented in Table 1. Part of the produced foam is immediately decanted to fill a Plexiglas cylindrical test container up to its top and is then allowed to drain freely. Ambient temperature during drainage is maintained at 30 ± 1 °C. The Plexiglas test container has 7 cm internal diameter and 26 cm height. A schematic layout of the experimental configuration is presented in Fig. 1.

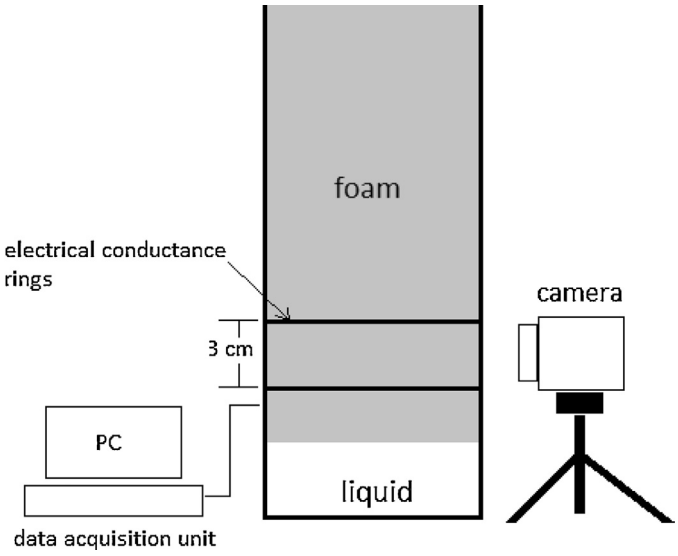

Fig. 1. Schematic layout of the experimental setup.