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In situ measurement of the permeability of foam films using quasi-two-dimensional foams

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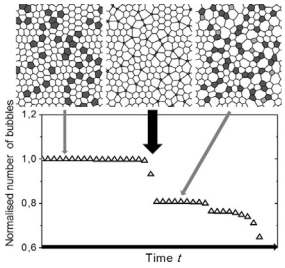
HIGHLIGHTS

- We present a new method to measure the permeability of foam films in situ in a two-dimensional foam.
- We examine the influence of the liquid fraction and show that it can be taken into account through geometrical considerations only.
- We examine the influence of the gas and show that we recover results obtained in the literature at the scale of an isolated film.

GRAPHICAL ABSTRACT



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ABSTRACT

The gas permeability of the thin liquid films which separate neighbouring bubbles in a liquid foam plays a key role in foam coarsening. Different approaches have been developed in the past to measure the film permeability, relying on measurements either on individual films/bubbles or on bulk foams. While the first approach may not be sufficiently representative of a real foam film, the latter is hardly feasible due to a lack of quantitative description of the coarsening of bulk foams with non-negligible liquid content. Here we show that a good compromise between these approaches can be achieved by investigating the coarsening of quasi-two-dimensional foams. More precisely, we propose a particularly simple approach in which we follow the evolution of the number of bubbles of an initially monodisperse foam. In this case, a large number of bubbles disappear simultaneously, leading to a "catastrophic" event, which can be identified easily and accurately related to the film permeability. We demonstrate the potential of this technique by using aqueous foams stabilised by sodium dodecyl sulfate having different liquid fractions and containing different gases. The experiments are compared to Surface Evolver simulations.

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1. Introduction

Liquid foams consist of closely packed gas bubbles which are surrounded by a continuous liquid phase and stabilised by surface active agents [1,2]. They are inherently unstable, leading to a continuous growth of the average bubble volume with time either via the rupture of the thin films separating two bubbles ("coalescence") or via the diffusion of gas through the thin films driven by pressure differences between neighbouring bubbles ("coarsening").

In order to understand the coarsening behaviour of a liquid foam, one needs to couple the gas transport through a single film with the distribution of film sizes and bubble pressures in the foam. Many different experiments have been developed in the past aiming to measure the permeability of an isolated film ([3] and references therein). These include in particular the "bubble diminishing method" [4–7] and a variant in which a pressure gradient across the film can be imposed explicitly [8–11]. We can also cite experiments performed in 1D-foams (bamboo foams: collection of bubbles in a tube) [12]. Even though these approaches have been quite successful in linking the permeability of the film to parameters like the film thickness or the physico-chemical parameters (nature and concentration of stabilising agents, nature of gas, additives, etc.), they remain somewhat simplistic and non-realistic models of real foam films. The collective effects as well as the topology of the foam are crucial to understand coarsening. For example, in isolated bubbles, the pressure across the liquid film which drives the coarsening is directly linked to the radius R of the bubble by the Laplace law ($\Delta P = 4\gamma/R$, with γ being the surface tension of the liquid), while in a foam with polyhedral bubbles the same Laplace law links the pressure drop directly to the topology of a bubble (here, the number of neighbours).

In order to access the permeability of the films in real foams, light scattering or tomographic techniques have been successfully used [13] to measure the characteristic time for coarsening. However, no particular attention was paid to the determination of foam film permeability. It was generally considered to be a parameter which depends mainly on foam film thickness. In more recent results, a dependence on the monolayer permeability was reported, as in model films [14]. However, in the experiments of reference [14], only the bubbles at the surface of the container were monitored, which could prevent to extract the averaged permeability in the whole foam.

Here we propose the systematic use of quasi-two-dimensional (quasi-2D) foams as a good compromise between single film/bubble and real foam experiments. Such quasi-2D foams are obtained by squeezing a monolayer of bubbles between two transparent plates. They have been used successfully in the past to reveal important foam properties, their key advantage being their straightforward visualisation and accurate theoretical description [2,15]. In particular, Roth et al. [16] have recently reported detailed investigations into the coarsening behaviour of such quasi-2D foams with different liquid fractions. Duplat et al did an extensive study of the evolution of a 2D monodisperse foam towards the scaling state through coarsening [28].

Here we propose that these foams may be used in an even more straightforward manner by simply measuring the time evolution of the number N of initially equal-volume bubbles contained in the cell. Even highly disordered quasi-2D foams consist of bubbles which mainly have either five, six or seven sides [17]. Following von Neuman's Law (Section 3), the gas exchange between the bubbles leads to a shrinkage of the 5-sided bubbles and a growth of the 7-sided bubbles, while the volume of the 6-sided bubbles remain unchanged. If topological rearrangements during the initial coarsening stage are negligible, then all the initially 5-sided bubbles disappear at the same moment. At this point the number of bubbles drop dramatically, which can be easily measured using simple image analysis software like ImageJ. This phenomenon is shown in Fig. 1 using Surface Evolver simulations [18] and experiments.

In the following we describe this approach in detail. After a description of the experimental set-up in Section 2 we continue with a short introduction to the theory of 2D foam coarsening (Section 3). We then discuss experimental results obtained for aqueous foams containing different amounts of liquid and surfactants (Section 5.2), and different gases (Section 5.3).

We find good agreement between our results and those obtained by the diminishing bubble method for the permeability of the films. The simplicity of our approach makes it attractive to easily and accurately measure the permeability of foam films over a wide range of parameters.

2. Materials and methods

2.1. Experimental setup and procedure

To study 2D foams, we use a cell made of two glass plates separated by a uniform thickness of 1 mm. Before use, the cell is immersed in Deconex 22LIQ-x diluted 30 times during 10 h. Then, it is rinsed 10 times with tap water, 10 times with distilled water and 5 times with double-distilled water (Millipore system, $\sigma = 18.2\ \mathrm{m\Omega\,cm}$). It is then soaked in double distilled water during 10 h. The tubes are rinsed in the same way. We use new syringes for each experiment. The cell is watertight thanks to two rubber joints separated by a silicon joint which ensures the tightness but never enters in contact with the foam. This is important since silicone is hydrophobic and leads to bubble bursting upon contact.

The cell is first set vertically and filled with the foaming solution. We measure the injected liquid volume V_{inj}, which corresponds to the volume of the cell. A known quantity of liquid V_{liq} is then removed through a syringe placed at the bottom of the cell which puts the cell at a pressure below ambient pressure. A second syringe is connected to a balloon containing the gas of interest (air, argon or nitrogen). The balloon is partially deflated to ensure that it is at ambient pressure. The gas replaces the removed liquid creating monodisperse bubbles of radius between 0.5 and 1 mm depending on the experiment. This procedure allows controlling the type of gas, the bubble size which is fixed by the size of the syringe and the liquid content of the foam which is defined by the liquid fraction

$$\Phi = \frac{V_{\mathrm{inj}} - V_{\mathrm{liq}}}{V_{\mathrm{inj}}}. \quad (1)$$

In our experiments the liquid fraction varies between 2% and 10%.

Once the desired liquid fraction is achieved, the syringes are sealed and the cell is set horizontally. The horizontality is ensured by a three feet support adjusted using a bubble level. The cell is lit by a circular neon allowing a homogeneous lighting of the foam (Fig. 2). A video of the foam ageing is recorded using a digital camera (uEye, lens with a focal of 12 mm), which allows taking high resolution pictures of the foam (3840*2748 pixels) at 1 frame/min.

To analyse the pictures of 2D foams, we use homemade plugins implemented in the free software ImageJ. These plugins allow us extracting the number of sides, the area and the perimeter of each bubble from a given picture. Three main steps are accomplished during the image analysis. The picture is first thresholded using grey level intensity in order to separate the wet walls (dark pixels) from the gas bubbles (bright pixels). Each bubble, constituted of connected pixel, is tagged with a single identifier. Secondly, the pixels from the walls are scanned and attached to a bubble only if they touch a single bubble. This operation leads step by step to a skeletonised 2D foam. At the end of this operation, vertices are

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