FOAMS IN MICROGRAVITY

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1. Introduction

Ordinary aqueous foam, which is our main subject in this paper, needs no introduction. Who has not taken a few minutes to study its beautiful structure (figure 1) and to watch it change? If you do so, you may study it from at least three different perspectives:

- as a compacted heap of individual *bubbles* of widely varying shape and size.
- as a division of space by conjoined soap *films*, all slightly curved.
- as a network of *lines*, the so-called *Plateau borders* where the films meet.

The first description relates to the manner of formation of the foam, which can even be designed to produce highly monodisperse foams. The second is the key to its stability: how long will the films survive without rupture? The third description often comes to the fore in theories of physical properties, such as conductivity, drainage or the mechanics of solidified foam.

Plateau (1873) gave us the first coherent account of the basic rules to which the structure must conform, particularly for relatively *dry* foams, of low liquid content. Underlying these rules is the essential principle of the minimization of surface energy (usually under the constraint of fixed bubble volumes). Indeed, most of the static and quasi-static properties of a foam may be explained by arguments which derive from that principle. It entails the Laplace-Young law (which we should celebrate in 2004/5 as this is its bicentenary year), and Plateau's rules for the junctions of films and borders (Weaire and Hutzler (1999)).

As the liquid content is increased, some of Plateau's strictures are relaxed. Whereas only fourfold confluences of borders are possible for the ideal dry foam, higher numbers may come together in stable junctions

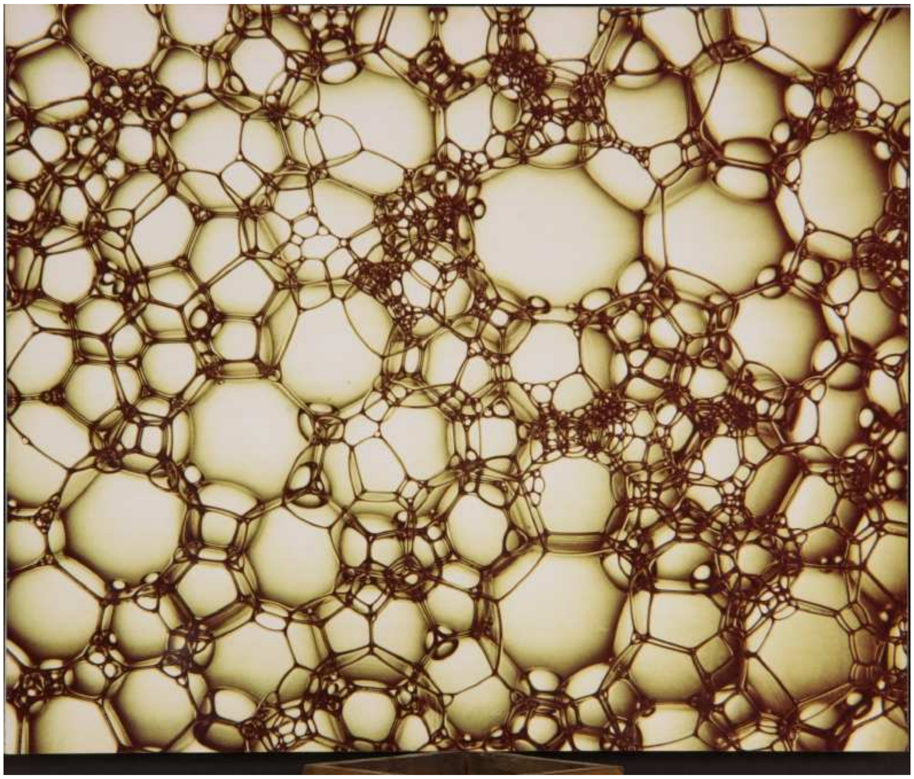

Figure 1. An aqueous foam as seen by the photographer-artist Michael Boran.

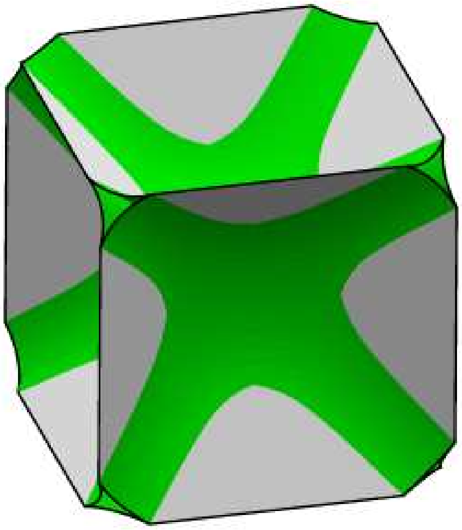

Figure 2. This wet eight-fold junction of Plateau borders is stable until the liquid fraction is reduced to an exceedingly small value, as shown by Brakke. Image courtesy of K. Brakke.

of the wet foam. We have not yet grasped the complexities of wet foam structures, except perhaps in two dimensions. Even in the carefully chosen special case of the symmetric eight-fold junction, shown in figure 2, progress has been slow since Weaire and Phelan (1996) raised questions about it, on the basis of experiment (see in het Panhuis et al. (1998)), neatly following the tradition of Plateau. Very recently, Ken Brakke has completed a masterful analysis which leads to the conclusion that a *finite but exceedingly small* liquid fraction Φ is required to stabilize this junction.

2. The Surface Evolver

Brakke is the originator and chief exponent of the Surface Evolver (Brakke (1992)), a suite of software which has been applied to such static problems. Its impact on this field is only part of a wider influence, whenever surface energy is dominant in physics and engineering (e.g. Collicott and Weislogel (2004)). As the crystallographer Alan Mackay has said

> The Evolver is a spectacular example of the effects of a gift to science which advances a whole field.

Figure 3 gives some further examples of the applications of the Evolver undertaken by our group. The most celebrated of these is the 1994

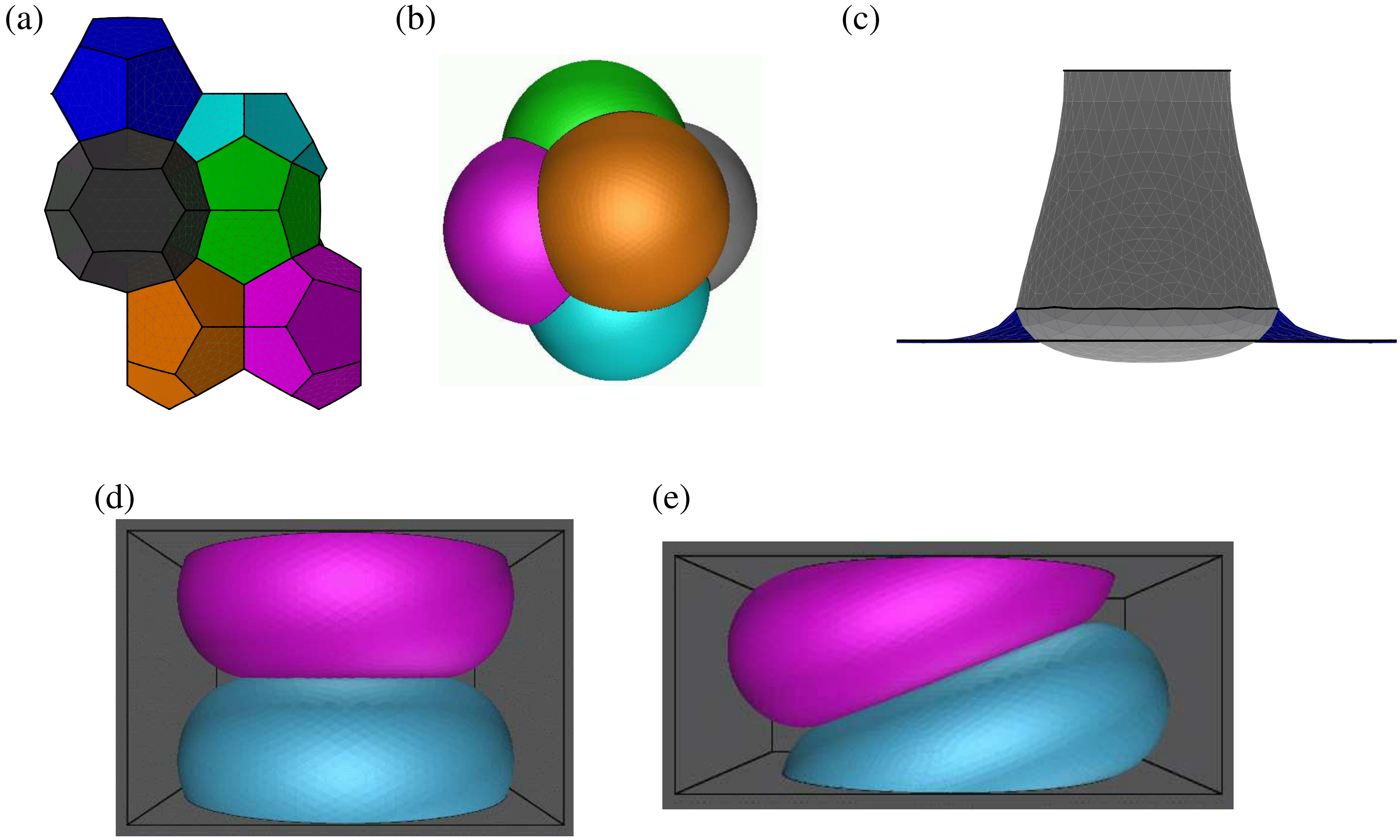

Figure 3. Examples of the use of the Surface Evolver. (a) The Weaire-Phelan structure which is conjectured to fill space with the lowest surface area. (b) A finite cluster of bubbles, used to investigate their local structure (Cox and Graner (2004)). (c) The meniscus surrounding a single bubble trapped between a glass plate and a liquid pool (Vaz et al. (2004)). (d) When two drops of oil are squeezed between parallel plates, there is a symmetry-breaking instability (e) at a certain critical separation (Bradley and Weaire (2001)).

discovery (Weaire and Phelan (1994)) of a structure of monodisperse dry foam that has a lower surface energy than that conjectured by Lord Kelvin (Thomson (1887); Weaire (1994)).

This structure has two different bubble shapes that fit together to form a structure of overall (body-centred-) cubic symmetry. It is about to be manifested in a spectacular building for the Beijing Olympics – the Water Cube – illustrated in figure 4. Its construction is based on

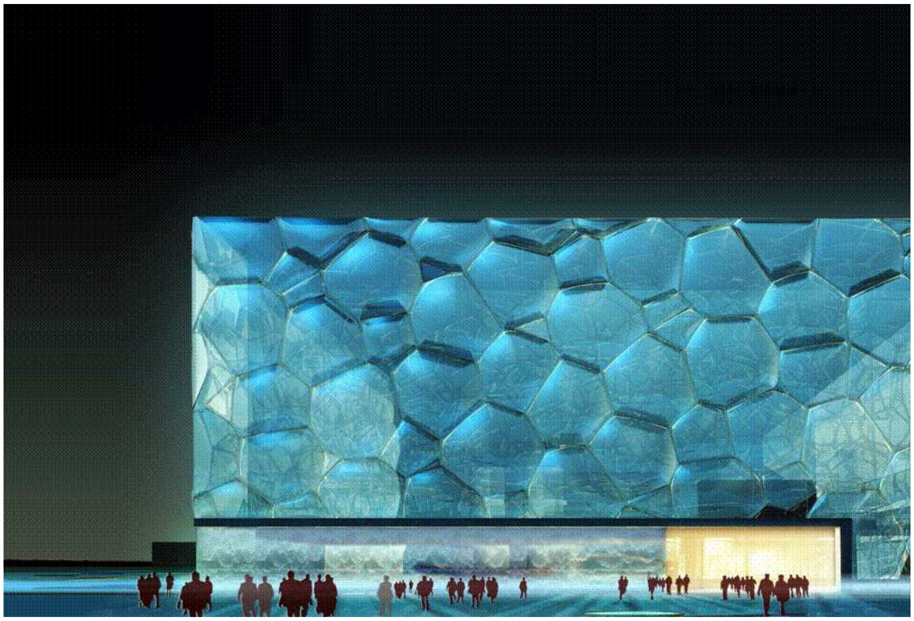

Figure 4. The designer's vision for the Beijing National Swimming Centre for the 2008 Olympics. The interior of its transparent walls consist of the Weaire-Phelan structure of figure 3(a). Image courtesy of Arup, PTW and CSCEC.

a network of steel beams, corresponding to the Plateau borders of the Weaire-Phelan structure. In analyzing its stability, the engineers must have repeated the kind of exercise undertaken by materials scientists for open-celled solid foams such as polyurethane (Warren and Kraynik (1991)). It should prove to be an inspiring instance of the harmony of scientific and aesthetic principles.

3. Debates over drainage

As anticipated in the closing chapter of the book of Weaire and Hutzler (1999), the focus of foam physics has moved from static to dynamic properties, related to drainage and rheology.

Drainage is the passage of liquid through the foam (mainly through the Plateau borders), driven by gravity o by pressure gradients. Its main properties are captured by a simple continuum theory expressed in a nonlinear partial differential equation.

Suppose we pour liquid steadily into the top of a foam: how fast does it travel downwards under gravity? Assuming Poiseuille flow in the borders, a relation may derived for which the velocity is

$$v \sim Q^{1/2}, \tag{1}$$

where Q is the flow-rate of added liquid. Although supported by several experiments (Weaire et al. (1997)), this was challenged (Koehler et al. (1999)), in favour of an index of *one-third.* It transpired that the discrepancy between the old and the new results lay in the use of different surfactants to stabilize the foam. Some of these produce relatively rigid surfaces (hence Poiseuille flow) while others leave the surfaces mobile (Durand et al. (1999)). In future, we will be more cautious in asserting generic properties!

4. Getting rid of gravity

Beyond a certain flow-rate, the steady drainage described above becomes unstable, giving rise to a slow convective motion (Hutzler et al. (1998); Vera et al. (2000); Weaire et al. (2003)). It therefore cannot be used as a proxy for the equilibrium structure of a very wet foam, which was part of the original motivation for its study. How then are we to prepare such uniform wet foams?

A static foam under gravity has only a very limited height of wet foam (if any) at the bottom. It may be estimated to extend to the height

$$h = \frac{l_0^2}{d} \tag{2}$$

where d is the bubble diameter and the capillary length is

$$l_0^2 = \frac{\sigma}{g\Delta\rho}. \tag{3}$$

Here σ is the surface tension, $\Delta\rho$ the density difference between gas and liquid and g the acceleration due to gravity.

The rest of the foam is essentially dry. Hence the ease of preparing dry foams and our frustration in wishing to study wet samples. Several strategies present themselves, and are summarized in figure 5. Of these, *density-matched emulsions* have been used by Mason et al. (1995) and others to probe static properties which are common to foams and emulsions, in theory. Another strategy is to use small enough bubbles that the wet foam thickness in eq. (2) above becomes considerable.

Thirdly, we may use steady drainage or attempt measurements in a short time-scale, before drainage has developed (Saint-Jalmes and Durian (1999)).

All of these suffer from limited applicability: hence the appeal of getting rid of gravity altogether, in drop towers, parabolic flights, rockets or space-stations.

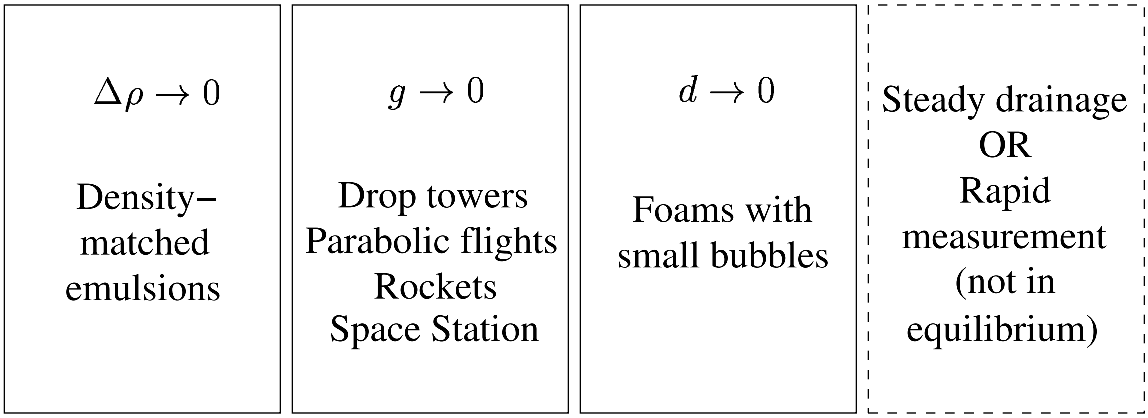

Figure 5. Strategies for preparing and studying wet foams.

5. Foams under microgravity

An honoured mention should be made of early space microgravity experiments on foams, particularly by David Noever (Noever (1994); Noever and Cronise (1994)), but these isolated efforts did not result in any coherent progress. Following the creation and operation of a Topical Team for this subject by the European Space Agency, there is some hope of a more systematic approach.

Currently the subject is being tackled in two ESA-sponsored projects. The first aims to utilize microgravity conditions to create homogeneous *metallic* foams (Wübben et al. (2002)). An example of a metallic foam is shown in figure 6. These materials are proving their potential in, for example, the automobile industry. The foamed metal should not suffer from drainage while in its liquid state, since this would lead to variations of density within the solid product (Banhart and Weaire (2002); Cox et al. (2001)). Obviously, microgravity sidesteps that limitation.

The second project is a study of *wet* aqueous foams in equilibrium, so that the processes of drainage, rheology and coarsening due to gas diffusion can be examined independently (Saint-Jalmes and Langevin (2004)).

6. Conclusions

For its satisfactory completion, the basic theory of the physics of foams needs to be extended to wet foams, initially in a state of static equilibrium. Describing dynamic wet foams will still be a considerable challenge. But it will reward success: churning, flowing wet foams lie at

Figure 6. An example of foamed zinc. The bubbly melt must be solidified quickly to retain the homogeneous structure, a stricture not required in the microgravity environment. Image courtesy of J. Banhart.

the heart of the chemical industry. As Weaire and Hutzler (1999) said, throwing down the challenge, a walk by the seaside on a stormy day is enough to excite curiosity. But it may be that the calmer environment of space is needed for the first progress in understanding wet foams.

Acknowledgments

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