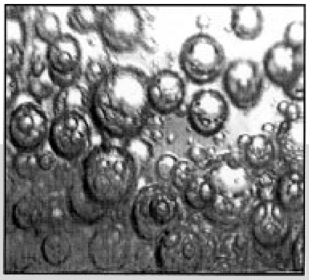
Foam Physics**

By *Denis Weaire**



The physics of foams faces interesting new challenges in metal foam fabrication. The range of possibilities may be greatly extended by proposed experiments in space.

1. Introduction

The physics of a foam is concerned with its birth, life, and death.

A process of foaming creates a gas–liquid mixture, as in Figure 1. It then pursues a life of gradual evolution. Finally it collapses, as thin films rupture spontaneously.

All three stages of its existence invite study. We have made considerable progress in understanding the eventful life of a foam. In this there is always some role for drainage, which is the transport of liquid through the foam, driven by pressure differences or gravity. In normal gravity it quickly reduces a *wet* foam to a *dry* one, with less than 1 % liquid. This dry foam is quite amenable to theory, so that most of the formalism that we have developed may be regarded as an expansion about the dry foam limit, in which the bubbles take the form of polyhedra with curved faces.

In a disordered foam, the gas in each cell has a different pressure and so the gas diffuses through the thin films that constitute the cell walls. In this way, the foam structure changes and coarsens, as cells are continually eliminated. This process, which is usually quite slow, is punctuated by sudden topological changes. They also play a key role in rheology, the deformation and flow of the foam under stress.

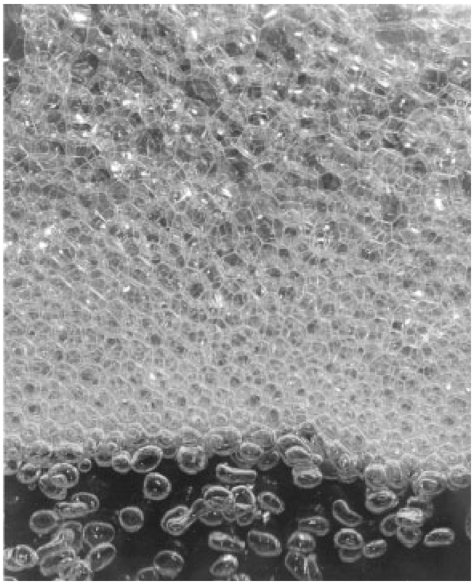


Fig. 1. Bubbles rising out of a liquid combine to make a foam, which is relatively wet close to the liquid surface (Courtesy of J. J. Cilliers, UMIST.)

By studying these various effects in isolation from each other, we have gained some understanding of them, at least for the dry aqueous foam.[1] Current research tries to put them together again and recognize their mutual effects. For example, how does coarsening affect drainage and vice versa? The key parameters determining such basic properties are the surface tension and the liquid viscosity. Nonlinear effects in surface tension and surface effects in viscosity may sometimes be important but structure, coarsening, and drainage can generally be described by the elementary model. For this reason one may speak with justification about the generic properties of foams, while always being ready to admit exceptions and necessary distinctions.

We also need to confront phenomena on faster time scales, where quasi-static models do not apply. And finally, wet foams remain largely unexplored, because the natural starting point is a wet foam in equilibrium, and drainage prevents us from making such a system in normal gravity.

Only very close to the underlying liquid is the foam *wet*, that is with a liquid fraction of more than, say, 15 % (slightly less than half of the maximum value in equilibrium). There is a useful approximate rule-of-thumb whenever the foam is in contact with underlying liquid. In equilibrium:

$$\text{thickness of wet foam layer} = l_0^2/d$$

where d is the average bubble diameter and l_0^2 is the squared capillarity length, which is the usual function $\sigma/\rho g$ of surface tension, liquid density, and the gravitational constant. For

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example, both l_0 in normal gravity and d are often of the order of 1 mm for aqueous foams, in which case the wet foam consists of only a single layer of bubbles.

Coarsening is the increase with time of the average size of bubbles. This is due to the diffusion of gas through the thin films, due to pressure differences. Generally speaking, larger bubbles have lower pressures and so this process continually eliminates the smaller ones.

In the final stage of the existence of the foam, the rupture of thin films takes over and causes it to collapse.

In recent years, this life history has been chronicled in some detail. It has come to be well understood only in the limit of a static, dry foam, as indicated in Figure 2. In part this limitation is due to experimental obstacles, since a wet foam rapidly drains in normal gravity. The wet foam is also more difficult to describe theoretically in any economical and systematic way.

The difficulties posed by gravity in studying the equilibrium of wet foams provide the primary motivation for some recent proposals for microgravity experiments under the auspices of ESA and NASA. At a more practical level, the microgravity environment should greatly extend the range of possibilities for the fabrication of new kinds of metallic foams, in terms of alloy composition, additives, pore size, and relative densities, as discussed below and elsewhere at this conference.

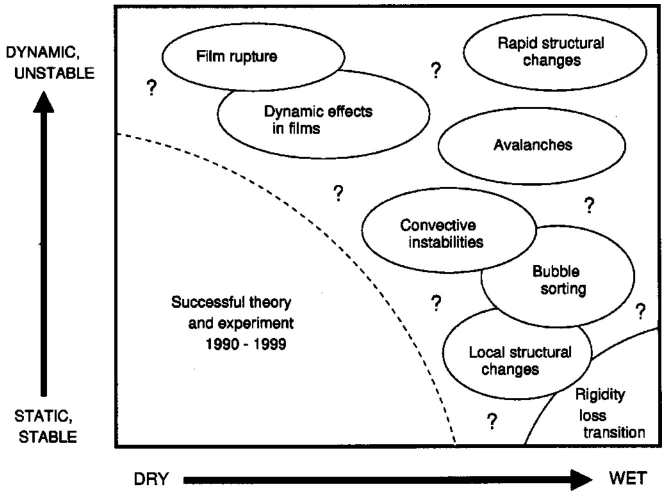

Fig. 2. *Many challenges remain for the general physics of foams.*

2. Getting away from Gravity

What is the effect of reducing gravity to (effectively) zero, in physical processes strongly influenced by it?

The question arises most commonly in fluid dynamics. Many important industrial processes involve convective flows, often to their detriment. Indeed, it is convective instability that has frustrated attempts to study wet foams by imposing uniform flow.

Can these convective effects be eliminated or more tightly controlled in space? This kind of question points to novel experiments in space. Their intent can be easily misconstrued. There can be little possibility of large-scale industrial processing in space in the foreseeable future, but in research the elimination of one factor is always valuable in determining the effect of others. Furthermore, we can confidently expect some surprises.

There have been occasional microgravity experiments performed on foam over past decades, conducted by American, Canadian, and European teams. For the most part, they have been quite preliminary and exploratory. They suffered from the poorly developed state of the theory at the time, which made it difficult to frame precise questions for experiment, or analyze results with any confidence.

For example, in the early nineties, foam floatation in a microgravity environment was investigated, using parabolic flights sponsored by NASA.[2] Foam floatation is an important industrial process, in which suspended matter is selectively removed from a liquid by adsorption in a foam. As expected, the experiments showed a strong dependence of the size of recovered particles on the strength of gravity, but there was no detailed analysis. Nevertheless, this was a useful pointer to the practical use of this technique in space, for waste treatment or biological sample processing. Similarly, a number of interesting experiments were carried out on foam drainage,[3] but the interpretation was rudimentary.

More recently, the group of M. Vignes-Adler in France has used parabolic flights to vary gravity, while creating and observing aqueous foams,[4,5] as in Figure 3. The detailed three-dimensional structure of samples of about 100 bubbles was captured by scanning with cameras with limited depth of field, so that it was even possible to identify the precise shape of every bubble.

3. Metal Foams

Another European group, located in the Fraunhofer Institute (Bremen), has embarked on the fabrication of metallic foams in microgravity[6] and it is hoped that these experiments will be the precursors of Space Station experiments.

Under normal gravity, the creation of a solid metal foam is a race against time. Once formed in the liquid state, it must be frozen quickly enough to avoid drainage, which would

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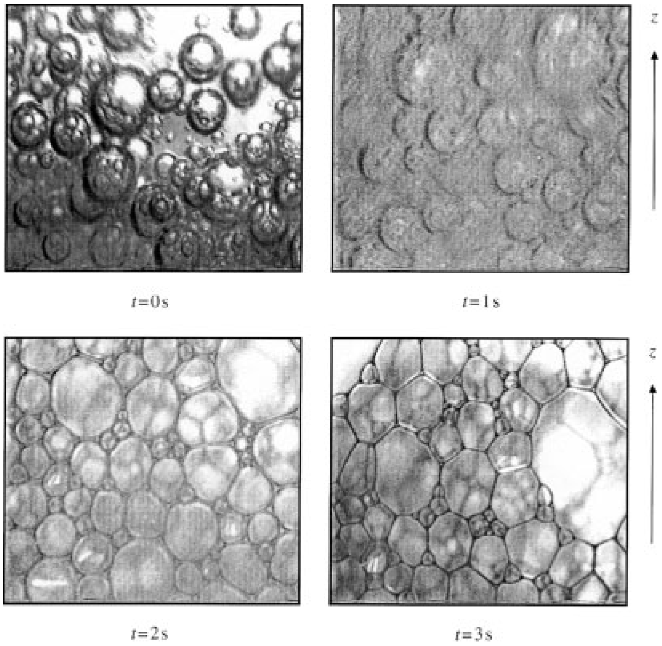

$t=0$ s $t=1$ s

$t=2$ s $t=3$ s

Fig. 3. Variation of a foam sample as gravity increases from zero to 1.8 g, as observed by the group of M. Vignes-Adler [4,5].

lead to inhomogeneity and collapse. Gravity is therefore the enemy, and various tricks are used to avoid its consequences, including the use of additives. In space we should be much more free to reduce additives and foam allow compositions not yet possible.

To gain a better sense of the limitations imposed by gravity, we have undertaken simulations[7] that describe its effect, in terms of the degree of inhomogeneity of the final product.

These will suggest directions for experiment both in space and on the ground. In the course of the ensuing comparisons we will find out whether the satisfactory progress that we have made with aqueous foams is really transferable to liquid metal foams.

It should be admitted that the attribution to liquid metal foams of the same basic properties as those of soap froths is plainly naïve: phase separations, additives and oxides are all thought to play important roles in making metal foam fabrication possible in practice. There is little understanding of their effects, in acting as surfactants and enhancing viscosity. As the practical uses of these exciting new materials begin to be identified, it may be time to begin to analyze the physics of the fabrication of metal foams in some detail.

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[1] D. Weaire, S. Hutzler, *The Physics of Foams*, Oxford University Press, Oxford **1999**.

[2] D. A. Noever, *J. Spacecraft and Rockets* **1994**, *31*, 319.

[3] D. A. Noever, R. J. Cronise, *Phys. Fluids* **1994**, *6*, 2493.

[4] C. Monnereau, M. Vignes-Adler, B. Kronberg, *J. Chim. Phys.* **1999**, *96*, 958.

[5] C. Monnereau, M. Vignes-Adler, *Phys. Rev. Lett.* **1998**, *80*, 5228.

[6] J. Banhart, F. Baumgärtner, S. J. Cox, B. Kronberg, D. Langevin, S. Odenbach, D. Weaire, T. Wübben, in *Proc. 1st Int. Symp. Microgravity Research & Applications in Physical Sciences and Biotechnology*, ESA Publications, ESTEC, Noordwijk **2001**, p. 589.

[7] S. J. Cox, D. Weaire, *Eur. Phys. J.* **2001**, *14*, 87.

[8] S. J. Cox, G. Bradley, D. Weaire, in *Proc. 2nd Int. Conf. Cellular Metals and Metal Foaming Technology (MetFoam2001)* (Eds: J. Banhart, M. F. Ashby, N. A. Fleck), MIT-Verlag, Bremen **2001**, p. 63.