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FRONTIERS OF THE PHYSICS OF FOAMS

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Abstract

We review recent progress in the physics of foams. While substantial, it is mainly directed towards stable, static, dry foams. The expanding frontiers of the subject include the prospective use of microgravity to create stable wet foams. The ESA-funded project “Hydrodynamics of Wet Foams” is aimed at this objective.

1 Introduction

The science of foams attracts the attention of chemists, physicists and engineers. Broadly speaking, they focus on effects on very different length-scales. The chemist explores the complex phenomena at the surface of the thin films, where the surfactants reside. The physicist concentrates on the shape and topology of the cells formed by the bubbles when they press together (see figure 1). The engineer seeks continuum approximations, in which the individual cells have no apparent role. There is currently an increasing interaction between these three communities, which have much to learn from each other.

Industrial motivations point towards comprehensive models which can analyse and predict the behaviour of such processes as foam flotation in the separation of minerals, or the many cases in which gas and liquid are intimately mixed in vertical arrays of “downcomers” in the chemical and petroleum industries. Chemical engineers have aspired to produce such models in the past, but this purely empirical style of research can become lost in a sea of rather arbitrary equations and adjustable parameters. The physicist prefers to *reculer pour mieux sauter*, and strives to create experiments in which the key properties of a foam may be studied in isolation from each other. These are (see figure 2):

- **drainage**, the transport of liquid through the foam, driven by gravity or pressure differences;
- **rheology**, the response of the foam to stress, which may be solid-like or liquid-like, depending on the magnitude of the stress;
- **coarsening**, the growth of the average bubble size due to gas diffusion, which is akin to Ostwald ripening;
- **collapse**, the eventual fate of most foams, due to the rupture of thin films.

In each case, the structure of the foam plays a role. In particular, structural rearrangements (often described as topological changes) are often seen as the essential feature of the behaviour of a foam.

2 Industrial Perspectives

Foams and foaming pose important questions and problems for the petrochemical industry in general. As a material, foam is almost unique in that it can be a desired product or agent in a process while at other times it is an unwanted byproduct. In the petrochemical industry, liquid foams are an essential part of gas/liquid contacting processes such as distillation, absorption and treating. However, an over-production of foam in these processes can and does lead to efficiency loss and unwanted downtime.

As products, solid polymeric foams, such as polystyrene and polyurethane, find applications as insulation panels in the construction industry. Their combination of low-weight and unique elastic/plastic properties also make them ideal as packaging and cushioning materials. Research results which bear on applications such as these should also have potential applications in the beer, confectionery and food sectors.

3 Dry and Wet Foams

The most significant single parameter characterising a foam is the liquid fraction Φ_l. It varies from very small values to a maximum of about 0.35 (that is, 35 % liquid). At this point the bubbles come apart and static equilibrium is lost - we enter the related field of the “bubbly liquid”.

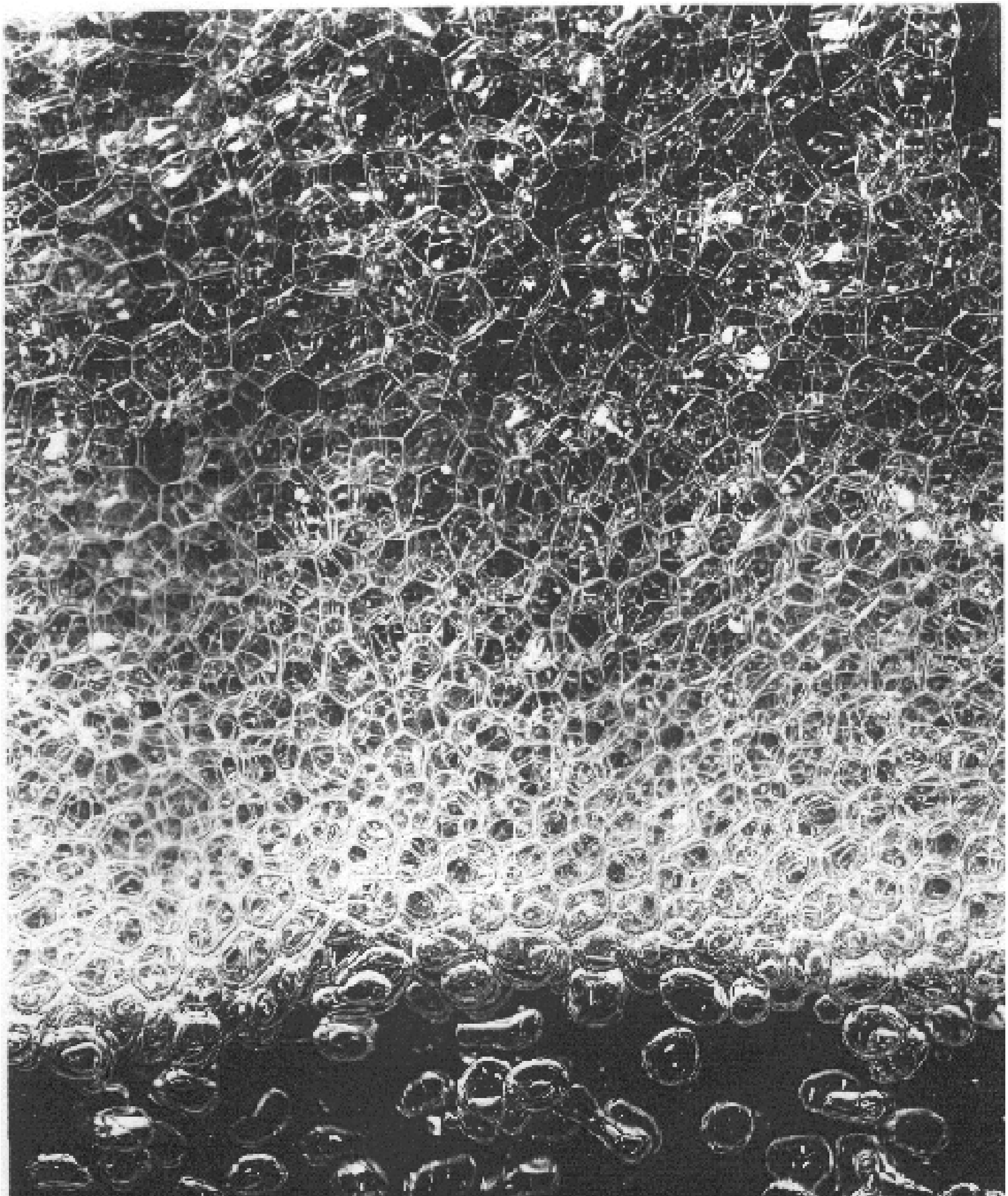

Figure 1: In an aqueous foam under gravity, only a thin layer adjacent to the underlying liquid is *wet*. Most of the foam is quite dry, so that the bubbles form polyhedral cells with curved faces (soap films). Most of the liquid is contained in the edges of the cells (Plateau borders). Photograph courtesy of J. Cilliers (UMIST).

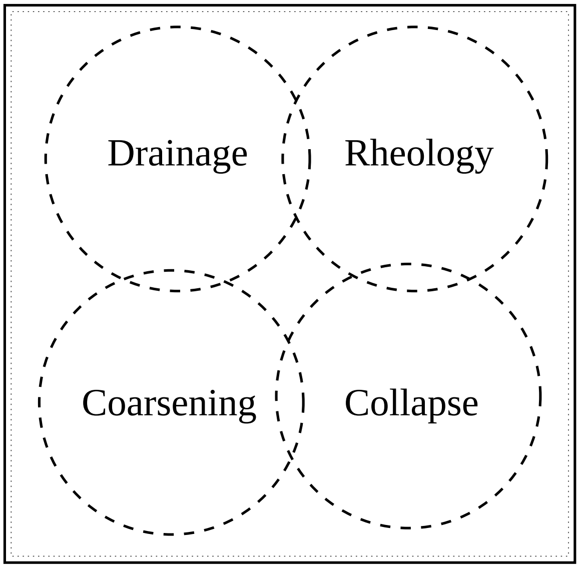

Figure 2: The key properties of a foam.

The distinction between a **dry** foam (say $\Phi_l < 0.15$) and a **wet** one is of paramount importance, in theory and in practice.

Under normal gravity, most foams in static equilibrium are very dry. Only very close to the underlying liquid (if any) does the foam belong to the wet regime. The dry foam is therefore readily amenable to experiment, and it turns out that it is also convenient for theory. Accordingly, in recent years experiment and theory (which contains large elements of computer simulation) have advanced together, to the point at which stable, static, dry foams may be said to be well understood, at least in terms of drainage, rheology and coarsening. Our understanding of collapse remains somewhat sketchy, and we may continue to struggle towards a generic picture of a process which depends very sensitively on impurities, often acting in combination.

4 Foam Drainage

The most striking results have been obtained for drainage. A model in which the liquid drains only through the Plateau borders (the liquid-filled channels between the bubbles), with a Poiseuille (or non-slip) boundary condition, works well in many cases (Weaire *et al* 1997). It is embodied in a non-linear partial differential equation for the liquid fraction (as a function of position and time), known as the Foam Drainage Equation (Verbist and Weaire 1994; Verbist *et al* 1996). This has a rich variety of solutions (Cox *et al* 2000); the most elementary is that of uniform steady drainage, where Φ_l is constant in position and time, and the average liquid flow velocity varies in direct proportion to Φ_l. The sudden ingress of liquid at the top of a dry foam produces a solitary wave whose velocity has the same dependence on Φ_l (the liquid fraction behind the front). It follows that

$$v \sim Q^{\frac{1}{2}},$$

where Q is the influx flow rate. The Foam Drainage Equation has a neat analytic solution for the profile of this solitary wave.

Just at the point at which confidence in this model was finally established by work in several research institutions (see, for example, Durand *et al* 1999), it was challenged by new results from Koehler *et al* (1999), which clearly indicated

$$v \sim Q^{\frac{1}{3}}.$$

This suggests an alternative model for flow through the Plateau border network in which the no-slip condition is relaxed, and dissipation is dominated by the junctions, or nodes, of these channels.

The discrepancy has been resolved as follows. Both groups, acting in the rather cavalier tradition of the physicist, used ordinary commercial dishwasher detergent to create their foams. It seems that the leading brands on different sides of the Atlantic (that is, Dawn and Fairy Liquid) have quite different surfactant properties! For the time being, this is being attributed to the relative values of surface viscosity, but this explanation remains to be validated and understood.

The search for a better understanding of the role of the surfactant brings us inevitably to an analysis of the *local* fluid flow of both the bulk solution and surfactant-coated free surfaces. Subtle chemistry and advanced computational fluid dynamics are involved, but the problems are not insurmountable.

5 Rheology

Briefly stated, the case of rheology is much the same: a clear picture exists of the quasi-static relation of stress and strain, but it needs to be extended to finite-strain-rate effects. The existing literature of the latter contains little more than shots in the dark.

Again we are drawn inexorably to the local scale, at which topological changes need to be described as *dynamic* processes, rather than essentially instantaneous changes, as in the quasi-static (low strain-rate) models.

Ahead lies an even more difficult regime, in which rates of shear are so high that individual topological changes cease to have any meaning. (Each local change cannot be completed before its locality is caught up in another one.)

6 Towards Wet Foams

Even the successful quasi-static models are limited to dry foams, by their own approximation and by the lack of experimental data which might allow validation for wet foams. To some extent it is possible to circumvent this limitation by using uniform, steady drainage to create a wet foam, albeit not truly in equilibrium. For example, this has been used to measure resistivity, up to about $\Phi_l = 12\%$ (Phelan *et al* 1996).

Beyond this point even this technique fails, due to intervention of an effect which is in itself intriguing - uniform drainage becomes *unstable*, and one or more convective rolls develop (Hutzler *et al* 1998; Vera *et al* 2000) - see figure 3.

This is not at all understood, and poses a good test problem for any theory which claims to combine rheology and drainage.

7 The Motivation for Microgravity Research

Our inability to conduct experiments on static wet foams (or even uniformly draining ones) under normal gravity is the dominant motivation for the prospective research in the microgravity environment.

Two European teams are preparing for such work. Both have arisen out of the Topical Team “Foams and Capillary Flows” coordinated by Trinity College, Dublin. The Fraunhofer-led project “Development of Advanced Foams under Microgravity” began in September 2000, and the Shell-led “Hydrodynamics of Wet Foams” was expected to begin shortly afterwards. It is understood that NASA has supported research which, while different in methodology and instrumentation, has similar goals.

For further details of the first project see Banhart *et al* (2000). In what follows, we shall give an indication of the work envisaged in the second project.

8 Hydrodynamics of Wet Foams

Some years ago, a *resistance profile monitor* was developed at Shell, for the measurement of the vertical profile of liquid fraction in an aqueous foam. It is based on the observation (supported by theory) that the resistivity of a foam accurately defines its liquid fraction (Weaire *et al* 1995). This instrument provided the early data on profiles under various conditions of drainage, which vindicated the Foam Drainage Equation.

It is proposed to produce a more robust and reliable form of this instrument for future research under microgravity, and to design experiments which will enter for the first time the regime of wet foams close to equilibrium. Parabolic flights will be useful intermediate steps in this programme.

9 Summary

The present state of the art is summarised in figure 4. Microgravity promises to take us from the *dry-static* to the *wet-static* square in, say, five years. Another ten may be required to complete all four squares. Only when that has been reliably achieved will we be able to model those industrial processes in which at least part of the foam is being rapidly churned up, in conjunction with the underlying liquid. The surf on the sea-shore is an extreme example of this challenge.

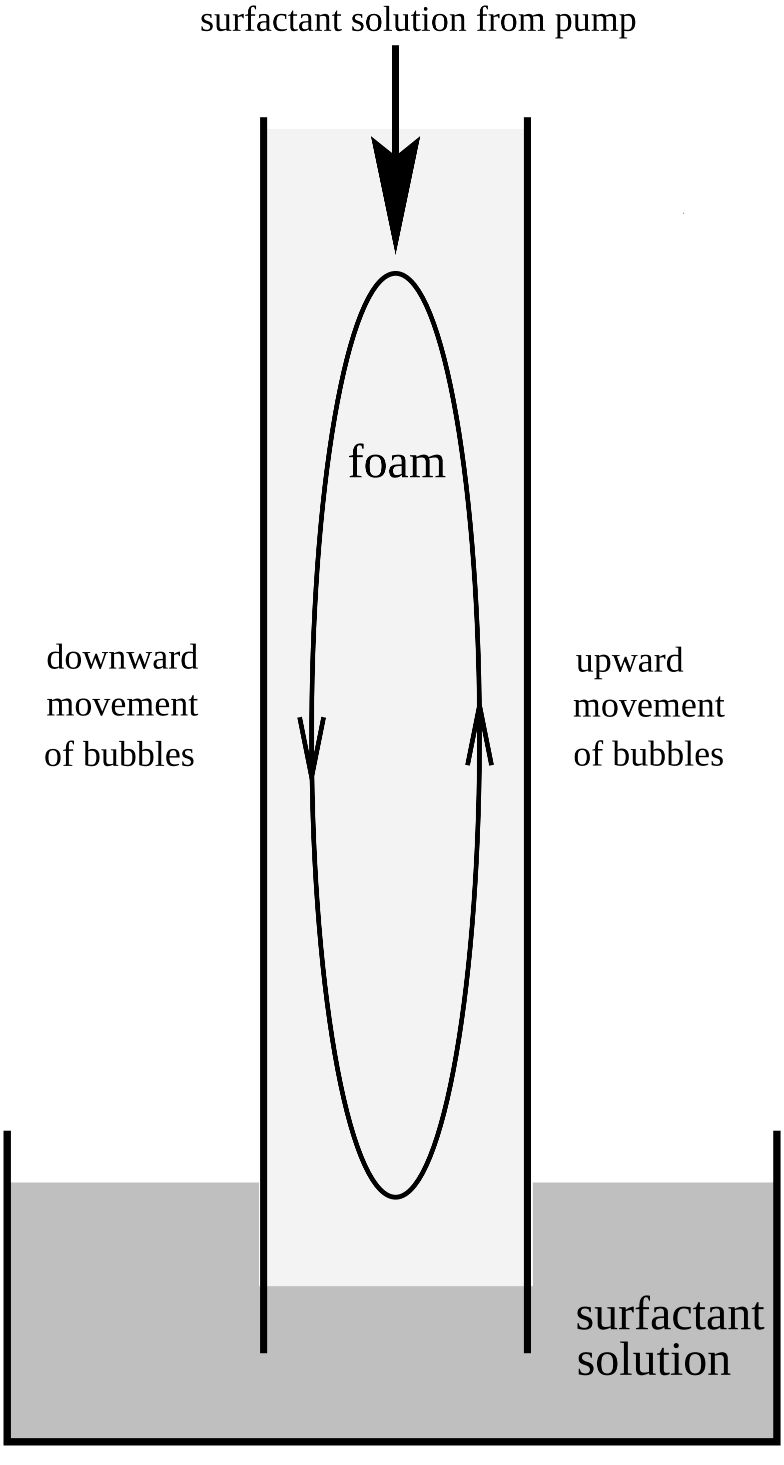

Figure 3: At high liquid flow rates, a convective roll develops.

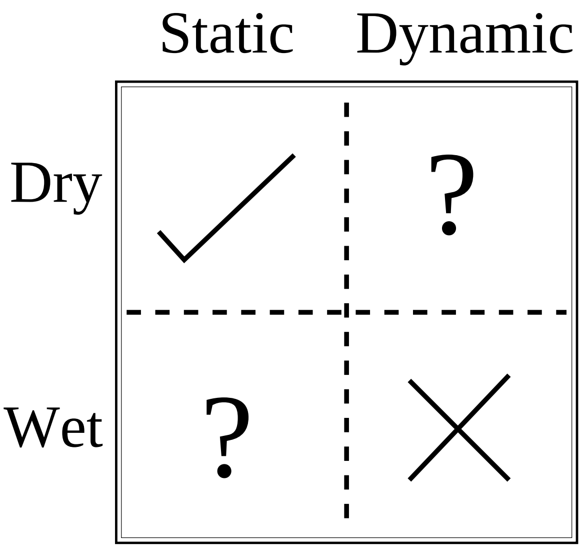

Figure 4: The state of the art in foam research.

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References

Banhart, J., Baumgärtner, F., Cox, S.J., Kronberg, B., Langevin, D., Odenbach, S., Weaire, D. and Wubben, T. 2000 Development of advanced foams under microgravity. In this volume.

Cox, S.J., Weaire, D., Hutzler, S., Murphy, J., Phelan, R. and Verbist, G. 2000 Applications and Generalizations of the Foam Drainage Equation. *Proc. R. Soc. Lond. A* **456**:2441–2464.

Durand, M., Martinoty, G. and Langevin, D. 1999 Liquid flow through aqueous foams: From the Plateau border-dominated regime to the node-dominated regime. *Phys. Rev. E* **60**:R6307–R6308.

Hutzler, S., Weaire, D. and Crawford, R. 1998 Convective instability in foam drainage. *Europhysics Lett.* **41**:461–465.

Koehler, S.A., Hilgenfeldt, S. and Stone, H.A. 1999 Liquid flow through aqueous foams: The node-dominated foam drainage equation. *Phys. Rev. Lett.* **82**:4232–4235.

Phelan, R., Weaire, D., Peters, E.A.J.F. and Verbist, G. 1996 The conductivity of a foam. *J. Phys.: Condensed Matter* **8**: L 475–L 482.

Vera, M.U., Saint-Jalmes, A. and Durian, D.J. 2000 Instabilities in a liquid-fluidized bed of gas bubbles. *Phys. Rev. Lett.* **84**:3001–3004.

Verbist, G. and Weaire, D. 1994 A Soluble Model for Foam Drainage. *Europhys. Lett.* **26**:631–634.

Verbist, G., Weaire, D. and Kraynik, A.M. 1996 The foam drainage equation. *J. Phys.: Condensed Matter* **8**:3715–3731.

Weaire, D., Findlay, S. and Verbist, G. 1995 Measurement of foam drainage using ac conductivity. *J. Phys.: Condensed Matter* **7**:L 217–L 222.

Weaire, D., Hutzler, S., Verbist, G. and Peters, E. 1997 A review of foam drainage. *Advances in Chemical Physics* **102**: 315–374.