DEVELOPMENT OF ADVANCED FOAMS UNDER MICROGRAVITY*

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Abstract

Possibilities for the investigation of novel foam systems under microgravity in the framework of a new research programme funded by ESA* are discussed. The emphasis is on the investigation of metallic foams, which can be made in various ways, although the field of interest is much wider: it also comprises other non-aqueous and aqueous liquid foams with a high liquid fraction (so-called „wet foams“).

Introduction

Exciting new industrial applications of foams have been developed in the past ten years. In particular, metal foams have evolved from a mere curiosity into a range of practical materials which are finding uses in cars and aircraft [1,2]. However, this new metal foaming technology still suffers from many deficiencies in comparison with, say, established polymer foam technology. Drainage problems are more serious owing to the high densities and low viscosities of liquid metals. Foam instability also limits reliable and reproducible mass production. Liquid foams are complex fluids which are particularly poorly understood if the liquid fraction is high. Under normal conditions the inevitable presence of gravity-driven drainage makes an investigation of coarsening, of the influence of surface active elements and of viscosity-enhancing additives very difficult, because of the rapid variations of foam properties induced by the gravitational flow. One would like to remove these limitations in order to generate improved models of the foaming of materials, especially metals. Microgravity could serve as a valuable tool to isolate some of the key factors which influence foam stability, namely surface tension and viscosity. Moreover, a unified approach in which foams of various materials, ranging from water and non-aqueous organic liquids to various metals, are investigated in a consistent manner would be desirable to create cross-fertilisation of currently unrelated research areas.

Foaming of Metals

Metals can be foamed by various methods, but all of these methods have in common that the foaming process takes place in the liquid state of the metal [3,4]. The properties of such a foam before solidification are similar in many respects to the properties of ordinary soap froth, which is well understood at this stage.

One method for foaming metals was invented a few years ago at the Fraunhofer-Institute in Bremen [5,6]. Foamed metal (Al, Zn, Pb) can be produced by the following recipe:

- a metal powder is mixed with a blowing agent, e.g. one mixes 99.5% aluminium powder and 0.5% titanium hydride powder.
- the powder mixture is hot pressed yielding a dense precursor material.
- the precursor is heated up to the melting point of the metal. As the metal starts to melt, the blowing agent releases gas. The melting body starts to expand slowly.
- the temperature of the foam is lowered to freeze the structure, resulting in a solid foam.

The process is in the state of a small-scale commercial exploitation by “Schunk-Honsel”, the collaboration of the two German companies “Schunk Sintermetalltechnik” and “Honsel AG”, and the Austrian companies “Alulight” and “Neuman AluFoam”. Schunk Sintermetalltechnik, one of the partners of the current programme, has built up production capacities for the production of small series of aluminium foam parts. However, it is planned to extend production facilities to cover potential mass market applications for metallic foams. As the quality of aluminium foam

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is not satisfactory at the moment and reproducibility of production processes still suffers from some deficiencies, a stronger involvement in fundamental research is considered necessary.

An alternative production route is to foam metallic melts directly by adding gas to them after carefully modifying their physical properties, namely their viscosity and, perhaps less important, their surface tension. The recipe for making aluminium foams by this route is then:

- add calcium metal or silicon carbide to an aluminium melt to make it *foamable*,
- add a blowing agent and stir vigorously, or blow air into the melt ,
- wait until the foam has expanded and cool down. Alternatively, the foam can be drawn off the surface of the melt by a conveyor belt.

This process has been commercialised by “Shinko-Wire” (Japan), “Hydro-Aluminium“ and “Sperre” (Norway) and “Cymat” (Canada).

Although metallic (and here mostly aluminium) foams are becoming more popular and companies are already producing this material, there are still some problems which have to be solved to satisfy the industrial demands:

- some foam properties have to be further improved for commercial applications,
- occasionally there are stability problems (collapse of foam) especially when making complex parts,
- the conditions which lead to good foaming properties are not sufficiently well known,
- new knowledge is often obtained in an empirical way instead of being based on a profound theoretical knowledge.

Therefore, we have launched a research programme which aims to investigate such foams under microgravity in an experiment on the International Space Station. As metal foams are believed to share their physics with other foams, the programme will include non-metallic systems too.

Investigation of foam formation

Metal foams have been characterised thoroughly with respect to their morphology, their mechanical properties and to other properties important for potential applications [1,2]. However, there is still only very little work (see e.g. [7-9]) on how the foam emerges from the liquid, how it changes with time and what mechanisms are responsible for its formation. The present paper is intended to help in closing this gap.

Monitoring the foaming process of liquid metals is much more difficult than doing the same with, for example, aqueous foams. Many of the observational techniques used for such foams cannot be applied, owing to the specific properties of liquid metals: they are hot, opaque, very reactive with oxygen and have a high electrical conductivity. These considerations rule out optical or resistometric methods, which are often used for investigating aqueous foams [10]. One can distinguish two kinds of possible techniques for investigating the foaming process of metals: ex-situ measurements and in-situ measurements. In the first case a foam is produced by heating up a precursor, thus initiating bubble growth and foam formation. After a given time the foaming process is interrupted by cooling and the resulting solid foam is characterised. By varying the time between the beginning of the experiment and the interruption of foaming one obtains a series of samples which reflect the various stages of foam evolution. The disadvantage of this approach is that it takes a long time to carry out such investigations and that the results suffer from a certain inaccuracy originating in statistical variations between the single experiments. Even if the starting materials for the individual foaming experiments were produced in the same way, each foaming experiment would turn out slightly differently due to effects such as accidental agglomerates of the blowing agent, structural defects in the precursor material and impurities. Therefore in-situ methods for characterising metal foams are preferred, in which a parameter characterising the foam is measured during the evolution of one single sample. Unfortunately, such measurements are very difficult to carry out and require quite sophisticated techniques. Two examples for such measurements will be presented here: volumetric measurements and in-situ radioscopy.

In the first case a metal foam column is produced in a vertical steel tube. The uniaxial expansion of the foam column is measured by means of a laser sensor. One obtains expansion vs. time functions as shown in Figure 1 for an AlSi7 alloy with various blowing agent contents. One sees a pronounced dependence of the expansion rate from the blowing agent content. Coming from a state without blowing agent an increase in expansion is achieved with rising contents of titanium hydride until saturation is reached for about 0.5 wt.%. This is actually the content of titanium hydride which is used in the production of aluminium foam at Schunk-Honsel and at IFAM.

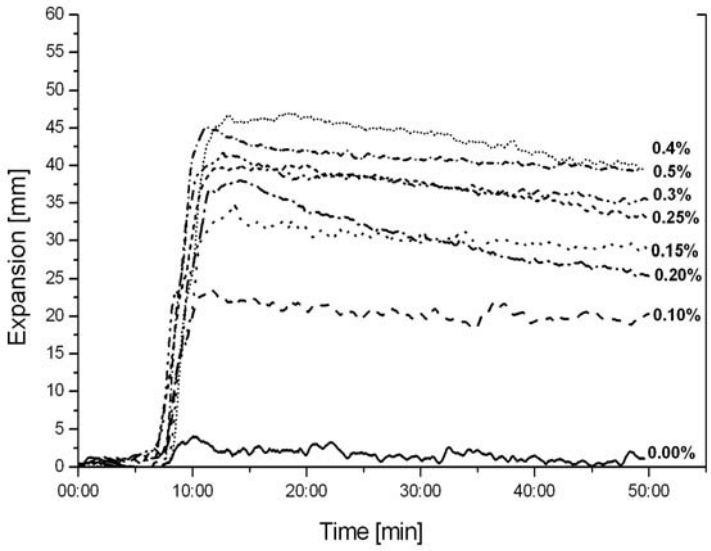

Figure 1: Time dependence of the expansion of AlSi7 alloys with varying content of blowing agent (from [11]).

Obtaining the volume of a foam is valuable information since it allows process parameters to be optimised and the quality of a given foamable material to be checked. However, it does not allow for an in-depth discussion of phenomena. A method which was successfully developed and applied only this year [11] allows information to be obtained about the internal structure of foams. Metal foam is expanded in a furnace which is equipped with two windows through which a synchrotron X-ray beam can be guided. The beam passes through the sample and casts an X-ray shadow of the foam structure on a scintillator screen which is read with a CCD camera. Resolutions of 40 μm were obtained in first experiments with a 1024x1024 pixel camera. Up to 3 images per second were taken. Due to the very low divergence of the beam generated by the European Synchrotron in Grenoble (ESRF), quite sharp pictures were obtained which allowed the identification of individual cell walls and features such as cell growth, deformation and rupture.

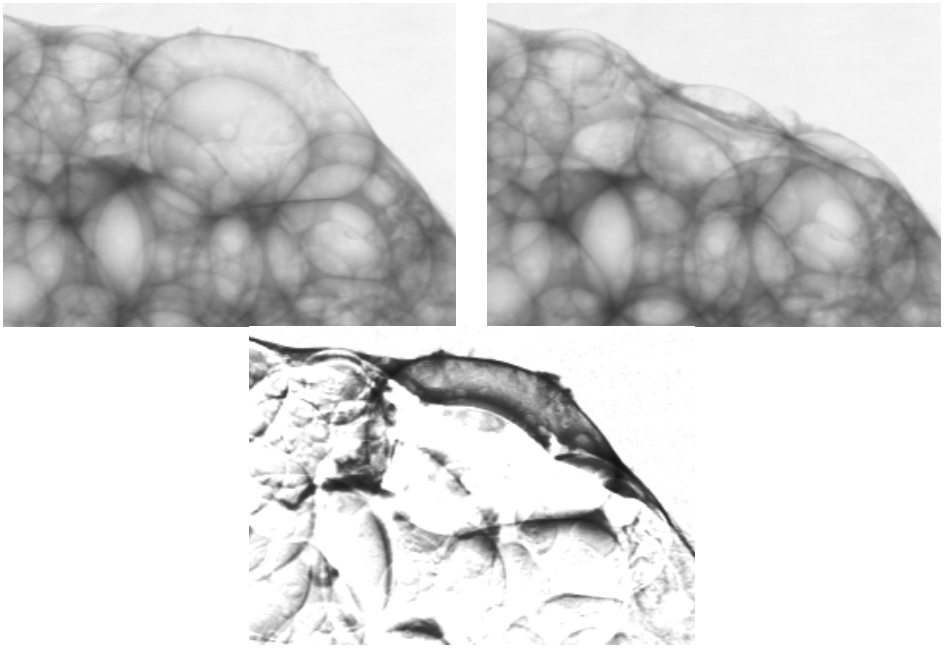

Figure 2:X-ray radioscopic images of an expanding aluminium foam. A series of 900 images was taken with a frequency of 2 per second. Two adjacent pictures and the difference of the pictures is shown. One can see the rupture of an individual cell wall (from [11], see also [12]).

Modelling the process of metal foam formation

Ideally, experiments in microgravity should be designed using models which are well tested in the terrestrial environment, to the extent that this is possible. In the present case, existing research has been conducted in an industrial/empirical spirit, and such models are lacking. Indeed, their necessary ingredients (the basic physical properties of these highly impure metal systems) are poorly defined. This situation calls for more systematic ground-based experiments, which can be used as a test-bed for modelling and establish the values of relevant material parameters.

A comprehensive model might include the initial expansion of the liquid metal and the subsequent effects of drainage due to gravity, coalescence, collapse and finally solidification. In developing this, one might hope to draw on the substantial body of established knowledge for aqueous foams [10]. However, we should be prepared for substantial revision when such models are tested. A system of liquid metal and solid particles may not be akin to dishwasher suds, after all!

As a first step, a one-dimensional simulation has been developed, in which an ideal foam is frozen from the top and bottom only. This geometry simplifies the theoretical analysis, and suggests that corresponding experiments would be valuable. This kind of calculation has already suggested a criterion for the avoidance of drainage [15], and hence the production of homogeneous foam under gravity. An example of a calculated profile of the final relative density of a metallic foam sample is shown in figure 3.

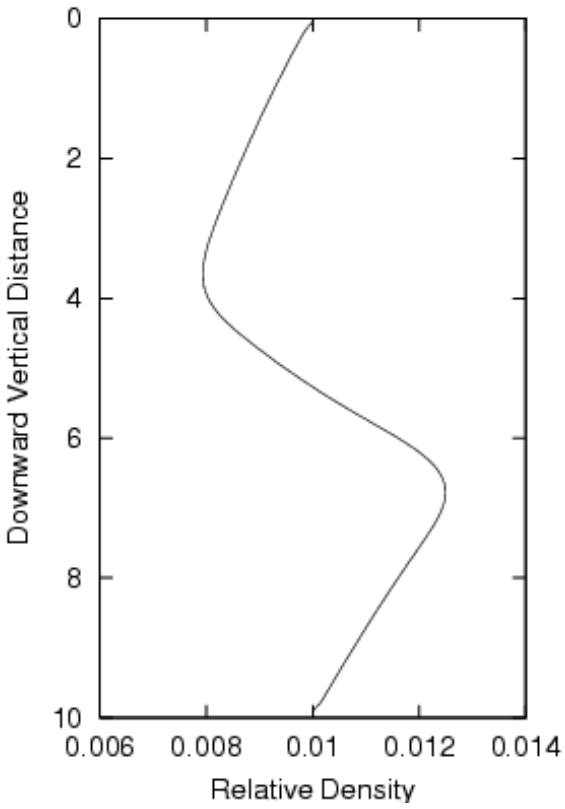

Figure 3: An example of a calculated profile of relative density for an ideal foam which is frozen from the top and bottom. Drainage under gravity induces an inhomogeneous solid product.

Necessity for microgravity research

Despite the recent advances in monitoring metal foams in real time, the exploration of the physics of foaming remains a very difficult task. Many of the difficulties are the same as those encountered for aqueous foams, but additional problems arise from the high temperatures in metal foams and the chemical reactivity of most melts. Moreover, as metal foams have quite high relative densities (usually between 10-20%) such foams must be considered as „wet foams“, thus making their treatment even more tedious.

One general problem in foam physics is that various effects are intertwined and difficult to study separately. This interdependence of various effects is explained in Figure 4 which defines the four principal effects and shows how they depend on each other.

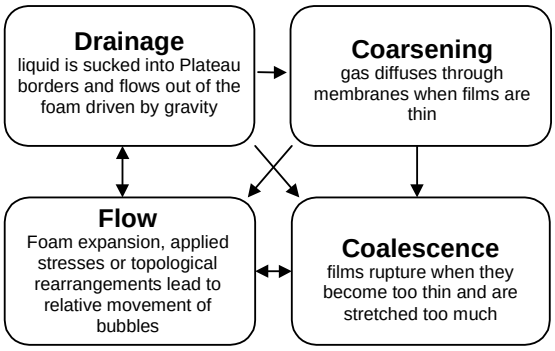

Figure 4: Interdependence of four principal mechanisms in foams.

Drainage causes a flow of liquid through a foam structure and consequently a drying out of the upper part of the foam. The loss of liquid makes the membranes (films) thinner. Thin membranes are then more prone to rupture, lose even more liquid by evaporation and are more penetrable by the gas in the cells. This clearly promotes coarsening and coalescence. Drainage, rupture and coalescence phenomena induce topological transitions and relative bubble motion in the foam. Flow in turn can induce rupture of membranes. One therefore encounters a complicated scenario in which many mutually interacting effects are present. One measure to simplify the situation is to avoid drainage. There are two strategies for this: either one might constantly supply fresh liquid to the top of a foam, maintaining a dynamic equilibrium in which the liquid fraction in the foam is constant [13,14,17], or one turns off gravity. The first method is clearly the easier, but as the liquid is constantly exchanged one possibly introduces hydrodynamic instabilities in the foam structure, especially at high feeding rates. Moreover, in the case of liquid metals the films are essentially stabilised by solid particles dispersed in the bulk of liquid and one would certainly have difficulties in maintaining a spatially-constant chemical composition in metal foams when circulating the liquid metal. Therefore, microgravity seems to be the preferable method for carrying out investigations on metal foams, despite the experimental difficulties (and costs) entailed.

Microgravity research programmes

Previous work

A first research programme on metallic foams under microgravity was launched by two of the authors of this paper in 1998 and includes the investigation of lead foams under microgravity in parabolic flights [16]. Lead (Pb) was chosen because only very low melting-point metals can be foamed in a few seconds, which is essential in view of the very short time (22 seconds) which is available under microgravity conditions. In the experiment, lead samples with an incorporated blowing agent are heated up very quickly. The samples are quite small: 20x20x1.8 mm^3 before foaming. After reaching the melting point of the metal (or the respective alloy used) the samples start to foam. The times are co-ordinated such that microgravity sets in when foaming starts. The foams freely evolve for about 20 seconds and are then air-quenched in the remaining 2 seconds of microgravity. Analysis is carried out on the solid samples. Samples are prepared under identical conditions in normal gravity conditions and compared to the microgravity samples. One result of the first experiment was that microgravity leads to slightly smaller and less oblate pores, as can be seen from *Figure 5:*

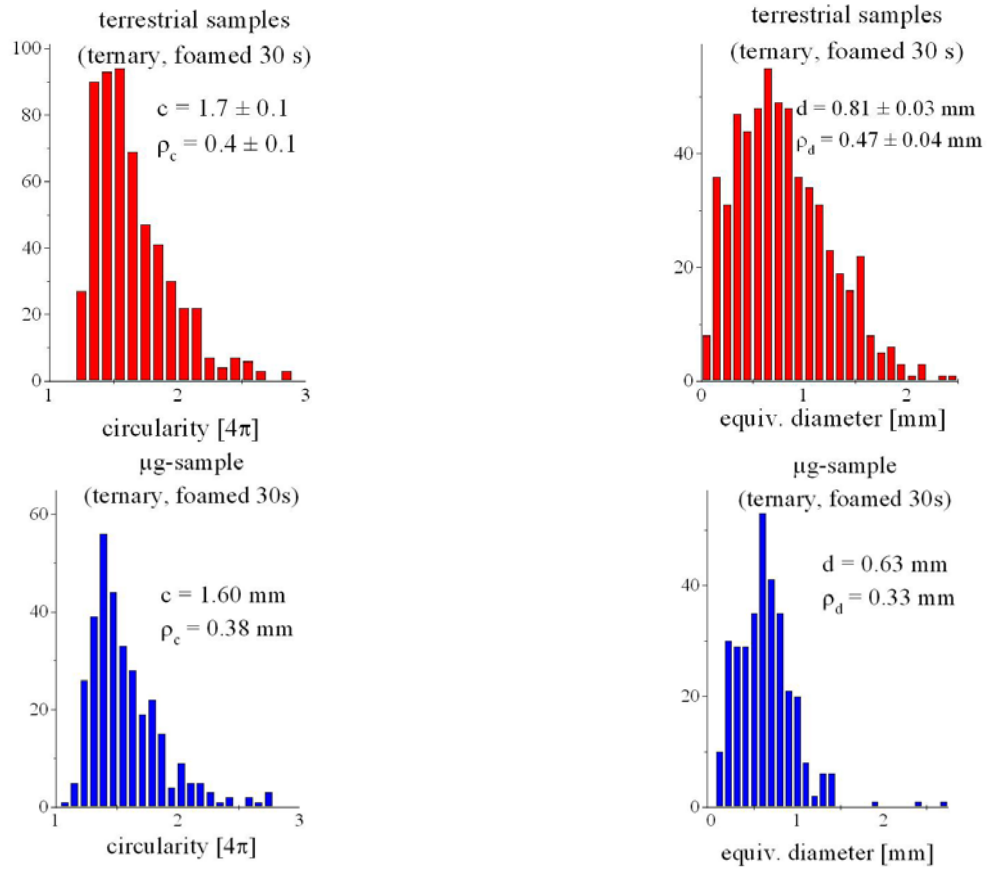

Figure 5: analysis of lead foams manufactured under 1g (upper panel) and "0g" (lower panel). Circularity (left) and equivalent pore diameter distributions are shown [16].

New research programme

The still ongoing microgravity research work on lead foams gives a first overview of the effects that can be expected in metal foams and shows the direction of future research. As the results are quite encouraging, the authors expect exciting new insights into the physics of foams - aqueous and metallic - as a result of the new ESA programme which started in September 2000. The main improvements in comparison to the current parabolic flight experiments will be:

- practically unlimited time of microgravity: this will allow the behaviour of foams to be studied over a long period (e.g. an hour),
- real-time observation of liquid metallic foams,
- the possibility to stimulate the foam and to measure its response.

The principal layout of the facility will be developed within the first two years of the programme. The details of the facility are therefore not yet available. However, some general specifications of the facility and the experiments can already be given:

- the facility is modularised, containing a furnace, a foaming tube, field and current generation unit and the foam diagnostics module. The modules are exchangeable.
- the range of materials to be foamed will be very wide, in order to gain access to as much data as possible
- variable atmospheric conditions can be chosen (vacuum, oxygen,...)
- possible diagnostic tools range from optical observation (video), light scattering and resistance measurement to inductance measurements and ultrasound probing. Building up the latter is a major challenge, because there is not much experience with such measurements.

The present plan is to be able to implement the 6 different types of experiment (E1-E6) schematically described in Figure 6.

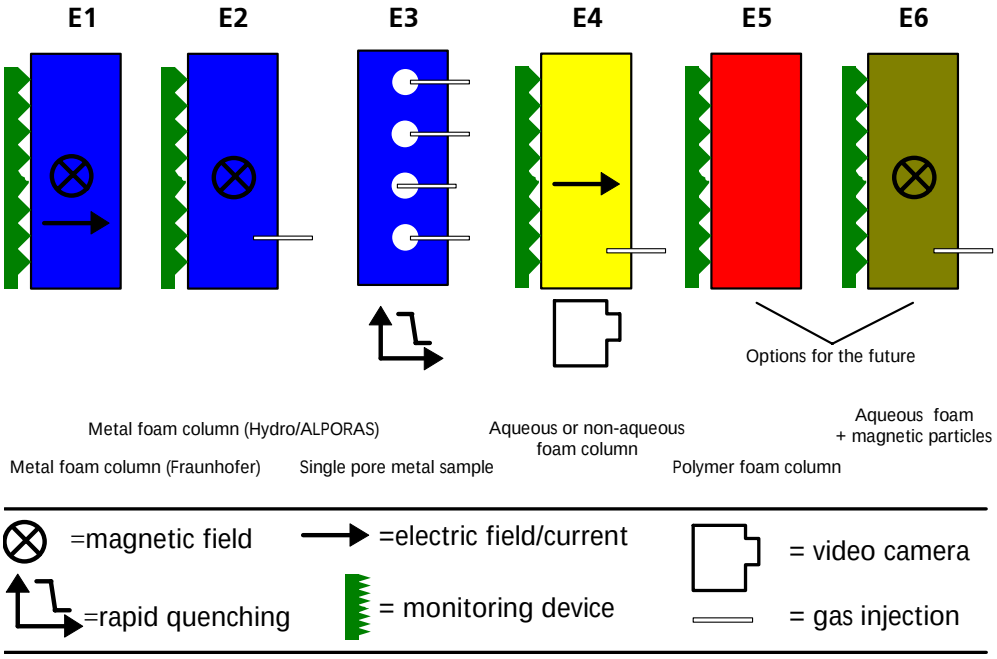

Figure 6: Schematic description of the six planned experiments.

E1: A metallic foam column is produced following the powder route. The evolution of the foam is monitored by means of a ultrasound or inductance device. Magnetic fields (up to 1.5 Tesla) can be applied to damp convective flows in the foam or to create a force in conjunction with an electric current (densities up to 3A/cm^2). The second option allows us to drag the bubbles to one or the other side of the foam and in this way to shear or to deform the foam and to observe effects of viscosity directly. Mostly zinc and aluminium alloys will be investigated.
E2: A metallic foam is produced by following the liquid foaming route already described.
E3: The container now contains a very clean metallic alloy melt into which gas bubbles (O_2, Ar) are injected at various locations. From our current knowledge it is predicted that two processes will occur which are important for foaming: there will be chemical reaction between the oxygen gas (O_2) and the metal, and there will be a diffusion of some of the alloying elements dissolved in the melt towards the fresh metal/gas interface. The sample is directionally solidified creating a chain of bubbles representing different stages of diffusion. The inner walls of bubbles inflated with oxygen will contain a layer of oxide which is believed to lower surface tension. The samples are analysed after flight (ex-situ) with respect to bubble size and shape, chemical composition of the interface zone between bubbles and metal (thus measuring the diffusion time scale) and thickness of the surface oxide layer.
E4: An aqueous or non-aqueous foam is generated by injecting gas into a liquid through glass capillaries. The type of surfactant is varied to explore the role of surface elasticity. The gas flow rate and the size of the capillaries are also varied to explore the role of bubble size. Electrical fields are applied to study the motion of isolated bubbles (for foams with a high liquid fraction). This will allow the determination of the surface electric potential of the bubbles.
E5: A polymer foam is created and analysed during and after foaming.
E6: An aqueous foam with suspended ultra-fine magnetic particles susceptible to magnetic fields is created.

Advancement of theory and modelling

The theoretical model outlined above captures many of the features which one would expect to be important in the combination of drainage and freezing that is involved in metallic foam formation. However, it remains to make a critical comparison with suitable experiments. The most important extension is generalisation of the model to three-dimensions. This will allow for cooling from all sides, rather than just the top and bottom.

The model currently allows an extension to include the effects of coalescence, but only in a crude manner. Improvements to the model may require a more sophisticated approach. In particular, it may involve the modelling of small particles lodged in the films, which are probably important to foam stability. Also significant is the formation of a molten liquid pool when parts of a foam collapse; this should also be included. Our goal is to create a flexible model for

such simulation, which can be of general utility in the future. In order for this to be realised, more systematic experiments are urgently required.

Summary

Foams are a wide and interdisciplinary working field and are worth being investigated in more detail owing to the interesting scientific aspects associated to them and their growing industrial significance. A unified approach which compares foams made from a variety of materials is highly desirable. Microgravity will serve as an important tool to decouple the various physical effects in foams make their investigation less complicated.

Acknowledgements

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