Eur. Phys. J. E (2014) **37**: 16
DOI 10.1140/epje/i2014-14016-3

THE EUROPEAN PHYSICAL JOURNAL E

Topical Review

Microgravity studies of aqueous wet foams

D. Langevin[1,a] and M. Vignes-Adler[2]

[1] Laboratoire de Physique des Solides, Bâtiment 510, Université Paris Sud 11, 91405 Orsay, France
[2] Laboratoire de Physique des Matériaux Divisés et des Interfaces, Bâtiment Lavoisier, Université Paris-Est Marne la Vallée, 77454 Marne-la-Vallée Cedex 2, France

Received 2 December 2013 and Received in final form 13 February 2014

Abstract. Foams and foaming pose important questions and problems for both fundamental research and practical applications. Despite the fact that foams have been extensively studied, many aspects of foam physics and chemistry still remain unclear. Experiments on foams performed under microgravity can be extended far beyond their counterpart where gravity is fully present (*i.e.* most experiments on Earth). They allow, in particular, observation of the wet foams obtained during the foaming process; on Earth, foams at this stage evolve too quickly due to gravity drainage and cannot be studied. This paper reviews the existing studies of foams under microgravity, which include studies in parabolic flights, in sounding rockets and in the International Space Station.

1 Introduction

Foams occur widely in nature and are used in important industrial processes and commercial applications [1–3]. Liquid foams are an essential part of gas/liquid contacting processes such as distillation and flotation of minerals. Solid polymeric foams, such as polystyrene and polyurethane, find applications as insulation panels in the construction industry and as packing and cushioning materials. Foams made with proteins are extensively used in food industry. We will discuss here foams made of packed gas bubbles in a liquid, typically water, and stabilized with an added surfactant.

The liquid volume fraction, ϕ, may vary from less than one percent (*dry* foam) to around 35% (*wet* foam) (fig. 1). At low volume fractions, the bubbles are deformed into polyhedra with both flat faces (bordering films) and curved faces (at the edges). Most of the liquid is confined to the edges called *Plateau borders* (PB), connecting three films and junctions or *nodes* connecting four PBs (fig. 2). When $\phi > \phi_c \sim 35\%$, the bubbles are spherical and move independently; for larger ϕ, the term *bubbly liquid* is used instead of foam.

Great progress has been made over the last thirty years in making the science of foams a sound and systematic discipline, with theories based on well-defined models being compared with well-characterized experiments. Properties of interest have included: the details of foam *structure* (the shapes and arrangements of bubbles), *coarsening* due to diffusion of gas (growth of large bubbles, shrinkage of small ones), capillary and gravity driven *drainage, rheology* and *coalescence* due to rupture of the films [1–3].

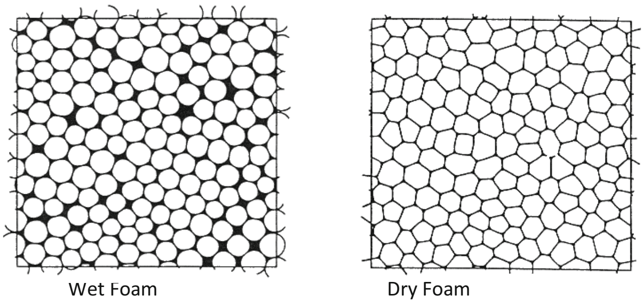

Fig. 1. Schemes for foams with different liquid volume fractions. Computer simulations of bidimensional foams, after ref. [1].

The methods which have been applied to these problems include: advanced computational *simulations* of foam structure, using the Surface Evolver of Kenneth Brakke; continuum *theory of drainage*, based on models of Poiseuille or plug flow in the Plateau borders; imaging and *tomography*; measurement of local liquid fraction using *conductivity* and *capacitance* probing; *multiple light scattering*, either with transmission measurements (DTS) or with diffusive wave spectroscopy (DWS), which probe foam structure and its evolution [3].

One of the difficulties encountered in foam studies is the variety of phenomena occurring at different length scales: *molecular* (surfactant monolayers at the air-water interface, $\sim 1\,\text{nm}$), *mesoscopic* (films between bubbles,

---

[a] e-mail: `langevin@lps.u-psud.fr`

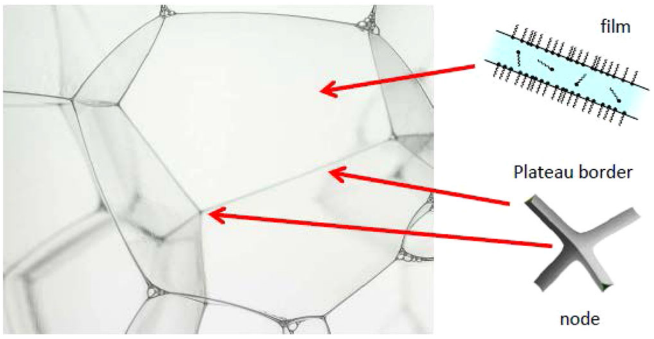

Fig. 2. An aqueous foam consisting of polyhedral bubbles and stabilized by surfactants. A liquid film separates the sides of the bubbles (top right) and Plateau borders exist at their corners (bottom right). The liquid films are stabilized by surfactant monolayers, surfactant molecules being represented by a circle (polar head), in contact with water, and a hydrophobic chain, in contact with air. The surfactant is also solubilized in water and present in the bulk liquid. From ref. [4].

$\sim 10\,\text{nm}$–$1\,\mu\text{m}$), and *macroscopic* (bubbles and Plateau borders, $\sim 100\,\mu\text{m}$–$1\,\text{cm}$).

Gravity plays an important role in the formation of foam and its subsequent evolution. Its primary effect is to cause excess liquid to drain rapidly away. When the foam is stable enough, it becomes dry and the gravitational force is balanced by a vertical pressure gradient in the liquid leading to a vertical profile of liquid fraction. The addition of liquid at the top of such a dry foam results in a solitary wave with an approximately constant profile during its downward passage. A sample undergoing such *forced* drainage can be used to study wet foams, but only up to about 20% liquid fraction, beyond which various dynamic instabilities (primarily convection) occur [5,6].

Theory predicts that the bubble growth laws (coarsening) are different in the wet and dry foam limit. However, comparison is nearly impossible on Earth because of the inherent instability under gravity of sufficiently wet foams. Only very recently, experiments on wet foams levitated by magnetic fields have been performed [7].

The same difficulty occurs with rheology, which can probe the very interesting transition occurring at ϕ_c where the foam changes from solid-like (finite shear modulus) to liquid-like (disconnected bubbles). This is a *jamming transition*, also encountered in other assemblies of randomly packed objects, such as emulsions, sand, clays, etc. [8]. In the case of foams, the 20%-35% range extends to the wet foam limit at which the foam becomes liquid. This range remains difficult to access on Earth, restricting present experiments to stable dry foams.

Apart from the above interesting issues, the study of wet foams is essential to understand and control foaming processes: foams are created in a transient wet state and evolve rapidly afterwards. All these open questions have motivated foam investigations in microgravity. Indeed, a micro- or zero-gravity study of wet foam hydrodynamics removes the various instabilities experienced under normal gravity. Specific plans arose out of detailed consultations with the European Space Agency (ESA), NASA and other national space agencies, ultimately aimed at the design of facilities in the International Space Station (ISS) for foam research. Under this platform, foam drainage, coarsening, rheology and stability are to be, in particular, studied.

In the following, we will first introduce the basic concepts in foam science, and then describe the different experiments performed in microgravity conditions and end with the experiments planned for the near future.

2 Basics of foams

Foams are dispersions of gas in liquid or solid matrices [1,3]. In order to generate a foam, an energy is needed to create the bubble surfaces, equal to γA, γ being the surface tension and A the area created. This energy is orders of magnitude larger than thermal energies and is not minimized: as a consequence, liquid foams are thermodynamically unstable. However, metastable configurations can be produced, in which each bubble takes a shape having minimal area for the given configuration: spheres for isolated bubbles and polyhedra (like the well-known tetrakaidecahedron proposed by Kelvin) in foams with small liquid volume fractions.

Because liquid foams are metastable, the use of stabilizing agents is required, which are generally surfactant molecules (fig. 2), but polymers, proteins or particles can also be used. The stabilizer role is to slow down the different mechanisms of foam ageing: drainage, coalescence and coarsening. Liquid foams *drain* rapidly under the influence of gravity until the liquid volume fraction ϕ reaches values smaller than a few percent. The foams evolve slowly afterwards due to coarsening and coalescence, until they fully disappear, typically a few hours later.

Foams made with liquids are mostly aqueous based. Organic liquids lead to more unstable foams which are mainly studied with view of how to avoid them because they can be damaging (in motor oils for instance). On the other hand, aqueous foams are widely used, for instance in detergency, food, cosmetics, fire-fighting (as barriers to oxygen), oil recovery (to exert pressure on the trapped oil) or flotation of minerals (bubbles behaving as carriers) [2].

Let us first discuss in more detail the main fundamental mechanisms which control foam stability.

2.1 Foam coarsening

Coarsening involves the transport of gas between bubbles of different sizes, leading to the growth of the average bubble radius R with time, $t : R \sim t^{1/2}$ [1,3]. Coarsening has the same origin as the phenomenon of Ostwald ripening in bubbly liquids, where the gas diffuses from the smaller to the larger bubbles due to difference in Laplace pressure. In the latter situation however, $R \sim t^{1/3}$ [9]. The law $R \sim t^{1/2}$ arises from the fact that in foams, the gas mainly diffuses through the thin films between bubbles for which the diffusion path is the smallest. The scaling laws for coarsening and Ostwald ripening are well established, but the prefactors are difficult to evaluate: the classical theoretical prediction by Lifshitz and Slyosov for Ostwald ripening might be wrong, since their theory is a mean-field approximation where the coarsening process is nonlocal. In the coarsening case, the foam is made of polyhedral bubbles and the evolution of single bubbles with different number of faces, N, is different (some grow, others shrink depending on N) [10].

A rough estimate of the characteristic coarsening time can however be obtained

$$t_{\mathrm{coars}} = \frac{R^2}{D_{\mathrm{eff}} f(\phi) h}\,, \tag{1}$$

where R is the average bubble radius, D_{eff} an effective diffusion coefficient, $f(\phi)$ the fraction of total area A of the bubble covered by thin films and h the film thickness [11]. The diffusion of gas molecules through thin films might be affected by the presence of surfactant monolayers, whose contribution can be significant, when their surface compression modulus E is high [12]. The surface rheology also affects the dynamics of bubble rearrangements during coarsening [13]. When $E > \gamma/2$, coarsening is arrested, as observed in foams stabilised by particles [14].

In the case of bubbly liquids, t_{coars} is proportional to R^3, inversely proportional to another effective diffusion coefficient, and also dependent on the liquid volume fraction [9]. The importance of the surface modulus E has been demonstrated in simulations [15].

Note finally that on Earth, foam coarsening is frequently coupled to foam drainage, and that the coupling is not easy to account for [16]. Microgravity conditions are therefore ideal to study the coarsening process.

2.2 Foam drainage

Bubbles with sizes larger than a few microns rise quickly due to gravity and the liquid is collected at the bottom of the created foam: this is the phenomenon of *drainage* (fig. 3).

As discussed, when the liquid volume fraction of the foam falls below about 35%, the bubbles are no longer spherical, they distort into polyhedra, the flattened regions being the liquid films. The liquid flows through the interstitial spaces between bubbles, which are composed of thin films, Plateau borders (PBs) and nodes (fig. 2). In very dry foams, the films are thin and the liquid flows mainly through the network of PBs.

With H the foam height, R the average bubble radius, ρ the liquid density, η its viscosity, g the acceleration due to gravity, the characteristic time of drainage is given by [17]

$$t_{\mathrm{drain}} = \frac{H\eta}{K\rho\, g R^2 \phi^{\alpha}}\,, \tag{2}$$

K is a dimensionless permeability constant of order 10^{-2} and α an exponent between 0.5 and 1. Both K and α depend on the mobility M of the surface layers protecting the bubbles, which itself depends not only on the compression modulus E but also on the surface shear viscosity [18].

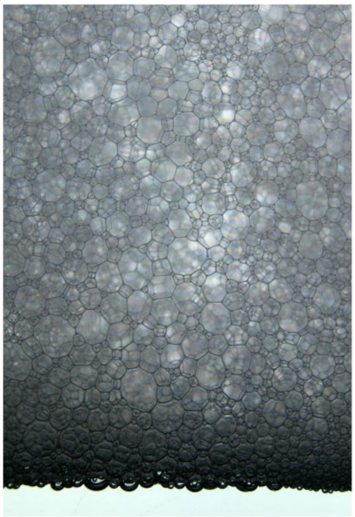

Fig. 3. Draining foam: the top of the foam is *dry* and composed of polyhedral bubbles. The bottom of the foam, which is in contact with the liquid, is *wet* and contains spherical bubbles. From ref. [4].

Foam drainage has been widely studied and is rather well understood. Nevertheless, our understanding is not complete, especially as both experiments and models are limited to the range of low liquid volume fractions ϕ ($\phi < 0.10$ for theory [19,20] and $\phi < 0.15$ for experiments [21]). Note that a connection to fluidized bed experiments has been made recently [22].

Besides the gravitational contribution, a capillary flow occurs whenever there is a liquid fraction gradient. In microgravity where only these capillary effects are present, the situation in a foam thus resembles the one in plants and tissues: Liquid pressure gradients can induce a diffusive fluid transport, coupled to macroscopic strains via the elasticity of the solid matrix (foams are poro-elastic materials, the elastic modulus being of order γ/R [1]). Studying capillary flows in foams can thus be an interesting approach to investigate the origins and speed of observed flows in plants and tissues [23], as well as for the development of hydraulically actuated soft systems and microfluidic devices.

Many theoretical aspects of imbibition experiments in microgravity have been discussed in ref. [24], starting from the drainage equations developed for Earth-based experiments. It was found that at any time, there is a well-defined maximum distance d covered by the imbibition fluid and given by (for low surface mobility M)

$$d = 0.8 K^{1/3} Q^{1/6} t^{1/2}, \tag{3}$$

where Q is the injected flow rate. Also, it was found numerically that for a given t and R, $\phi \sim Q^{4/5}$ and $\phi \sim Q$ for low and high interfacial mobilities M, respectively.

Fig. 4. Airbus plane used in parabolic flights experiments (left); time variation of the acceleration of gravity g (right).

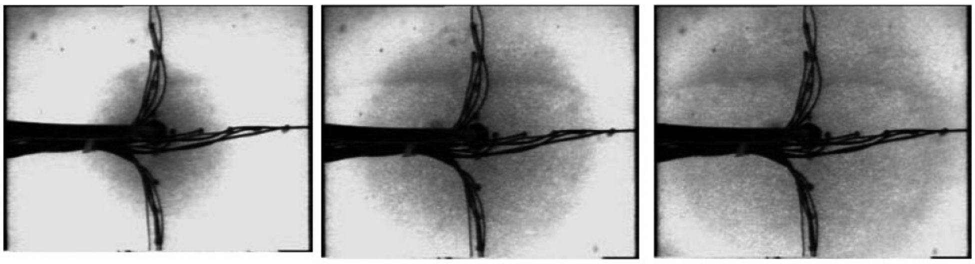

Fig. 5. Imbibition experiments in parabolic flights: picture of a foam at three different times, evidencing isotropic propagation. The liquid is injected at the centre, the wires are connections to electrodes; note that the wetter foam appears dark. CNES parabolic flight campaign, March 2005. Adapted from ref. [37].

2.3 Bubble coalescence

When drainage proceeds, the films between bubbles become thinner and can rupture, leading to bubble *coalescence*. So far, very little is understood about the main mechanisms of film rupture. Studies have suggested that coalescence in foams occurs once critical values of bubble sizes [25], liquid fraction [26,27] and/or applied pressure (or capillary pressure) are reached [28]. Even if these mechanisms are very different, it is difficult to discriminate experimentally between them since capillary pressure, liquid fraction and bubble size are linked. The different behaviours observed in the literature might also be due to different flow conditions and accordingly to different coalescence processes. It has been shown in particular that the rupture of entrained soap films is deterministic [29], at the difference of the rupture of equilibrium films [30]. A discussion of this complex issue can be found in ref. [31].

As coarsening, coalescence is coupled to drainage, which destabilises wet foams on Earth. Microgravity conditions are therefore ideal to study the coalescence process as well.

3 Experiments performed in microgravity conditions

3.1 Parabolic flights, drainage experiments

Parabolic flights are performed in airplanes in which microgravity conditions are obtained upon switching off the motors; 90 parabolas typically take place during one flight and for each parabola, 20–25 s of microgravity ($g \sim 0.1\,\mathrm{m\,s^{-2}}$) are obtained, between two equal periods of hypergravity ($g \sim 18\,\mathrm{m\,s^{-2}}$). A normal gravity phase separates each parabola, lasting one or two minutes (fig. 4).

Various parabolic flight campaigns have been conducted for testing foaming processes and to perform preliminary experiments of foam stability [32]. Early tests of devices intended to produce wet foams were performed by D. Durian in USA and A. Saint Jalmes in France, but described in unpublished reports. The stability of PBs junctions in wet foam conditions was also investigated and shown to be consistent with theory (junctions unstable on Earth become stable in microgravity conditions, once enough liquid is present) [33].

Other experiments were dedicated to the study of foam capillary drainage. Dry foams can be produced during the hypergravity period, after which the liquid can be injected in the foam and its propagation studied. The first imbibition studies in microgravity dealt with single layers of bubbles (2D foams) [34,35]. As predicted by theory, these experiments showed that foam capillary imbibition is a diffusing process. Experiments with 3D foams were made later, focusing first on the liquid front position [36]. Differences due to the surface chemistry were evident: for mobile interfaces, the liquid front spreads faster than for the rigid ones, in agreement with simulations [22]. In more recent experiments, the variations of ϕ in time and space were monitored, by coupling electrical conductimetry and light transmission [37]. In fig. 5, one sees that the liquid front propagation in the dry foam is isotropic under micrograv-

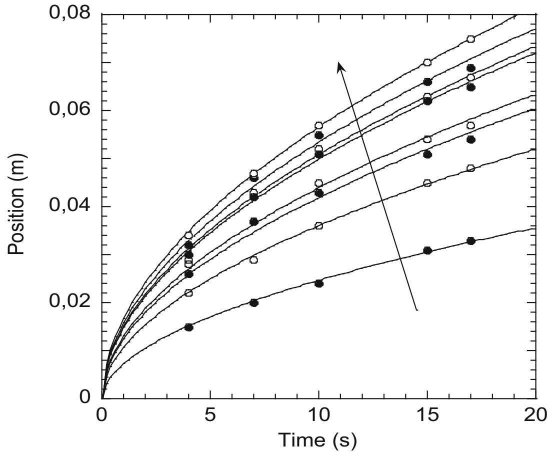

Fig. 6. Liquid front position as a function of time, for different injection flow rates. The arrow indicates increasing flow rates; the data are well fitted by a $t^{1/2}$ function (solid lines). Adapted from ref. [37].

ity conditions (different from Earth, where liquid moves more quickly in the vertical direction). This is because in microgravity, capillarity is the only driving force.

The front position *versus* time, for different injection flow rates is reported in fig. 6. Solid lines are fits with a $t^{1/2}$ function. As predicted by simulations, square root behaviour was found, confirming the diffusive nature of the liquid propagation in microgravity. The dependence of the prefactor with the flow rate Q follows well the expected law (in $Q^{1/6}$, see eq. (3)). The permeability K found using eq. (3) is in good agreement with other results. For this front propagation, ϕ was less than 1%. It is worth noting that, even if only capillarity is acting, the agreement between the models and data shows that the flow behavior is independent of the driving force.

Higher liquid fractions, up to 30%, can be obtained by imbibition in microgravity, without the usual convective instabilities found on Earth. In normal gravity conditions, if the flow rate is too high (above the instability threshold), the foam can no longer accommodate the gradient, and the structure destabilizes in order to transport the fluid at the imposed flow rate [5,6]. At the high liquid fractions created in microgravity conditions (> 20%), it was found that the classical drainage models overestimate the permeability, as some of their basic assumptions are no longer valid. For example, the volume of the nodes is no longer negligible [37].

3.2 Maxus flight, tests of the stability cell

Sounding rockets such as the Maxus rockets can obtain much longer microgravity periods, about fifteen minutes (fig. 7). The experiments performed between 2001 and 2005 on such flights confirmed that foams stabilized by surfactants could be produced in microgravity and were stable [38,39].

As in the parabolic flight experiments, were required cells which allow the measurement of the local wetness or foam density. For this purpose, a multipoint array instrument for conductivity measurements combined with diffusive transmission spectroscopy (DTS) was built. It was then possible to monitor at the same time the liquid content and the bubble size. Multiple scattering of coherent light (DWS: Diffusing Wave Spectroscopy) was also foreseen for the study of the rate of bubble rearrangements that characterizes foam dynamics [40].

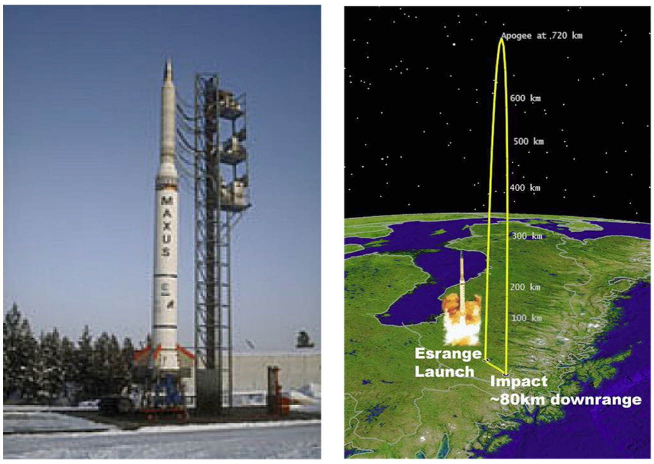

Fig. 7. Maxus rocket (left) and scheme of the flight performed (right).

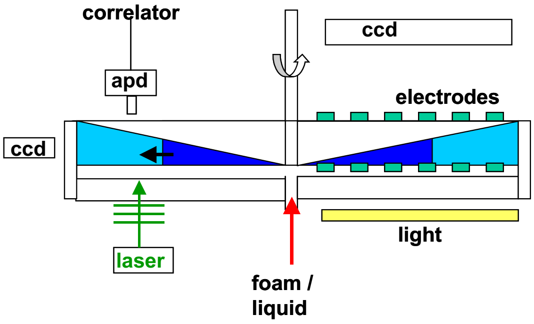

Fig. 8. Microgravity cell, side view.

Because the ESA-NASA program involved rheology studies, a special microgravity cell was first designed to perform both drainage and rheology studies. The cell was cylindrical, with top and bottom plates able to rotate either simultaneously (to study drainage) or to remain independent, the upper plate remaining fixed (to study rheology). The cell possessed a suitable combination of the two types of diagnostics, conductivity and DTS/DWS (fig. 8).

A Maxus flight performed in 2005 allowed to obtain preliminary drainage data [41]. The cell design was subsequently abandoned due to its elevated cost.

3.3 ISS Experiments. Foam stability

In ISS, the duration of microgravity is not limited, making this facility ideal for the study of long evolution processes, such as foam coarsening or stability.

Earlier experiments showed that foams stable on Earth were also stable in microgravity (sects. 3.1 and 3.2). It

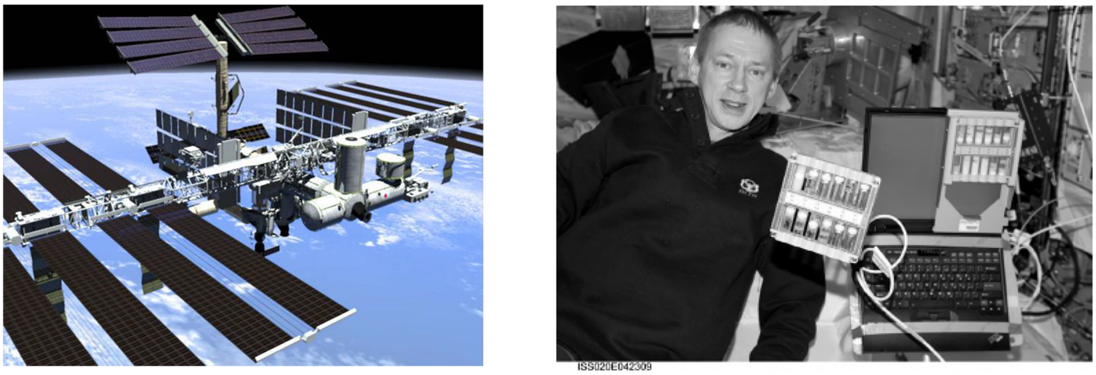

Fig. 9. Astronaut Frank de Winne on the ISS. A rack is free floating in the center of the picture. A second rack is placed in front of a computer screen for backlight illumination during video recording.

was then decided to check the stability of foams, unstable on Earth, under microgravity. The stability of aqueous and nonaqueous foams both on Earth and in microgravity was compared [42]. On Earth, the lifetime of a foam is limited by the free drainage: when the liquid films become thinner, they eventually break, and the foam collapses. In microgravity, this process is absent and foams containing large amounts of liquid can be studied for longer time. Different solutions were studied, containing surfactants, proteins, anti-foaming agents or silicon oil.

The first ISS mission took place recently, benefiting from a flight opportunity in 2009 during the stay of astronaut Frank de Winne (fig. 9). Sixty samples were studied, with liquid volume fraction of 30%, close to the jamming transition. These samples consisted of solutions of various surfactants (SDS-anionic, TTAB-cationic, Tween 20-nonionic) some of them very dilute. Also studied were dispersions of silica nanoparticles, solutions of various proteins (lysozyme, lactoglobulin, casein) and anti-foaming agents (Rhodorsil).

Generally, the foamability was much larger on the ISS than on Earth. Moreover, the foams showed a remarkable stability in the ISS. A striking result is that nonfoaming solutions on Earth lead to significant amounts of foam in space, even when the antifoaming agent is present. This behavior was not unexpected [43], but needed confirmation. The amount of foam decreased slightly in about ten seconds, after which all the foams were stabilized and no evolution was observed.

Microgravity experiments allowed studies on foams with liquid fractions around $\phi = 30\%$ to be performed. On Earth, such materials are unstable because the thin films between bubbles drain very quickly, allowing faster coarsening and facilitating coalescence. In microgravity, the liquid fraction is so high that the bubbles can keep a quasi-spherical shape which minimizes free energy and which slows down capillary drainage, coarsening and coalescence. Bubble coalescence events are nevertheless sometimes seen, but after some time, bubbles motion stop and the foam no longer evolves.

It is probable that the efficiency of the antifoam agents is reduced because the hydrophobic particles that they contain remain smaller than the thickness of the films between bubbles. Indeed, the agents destroy the foams by bridging the foam films and rupturing them via a dewetting mechanism. The buoyancy effect bringing the particles in the films is also absent [43].

Proteins also behave differently: protein solutions foam much better in microgravity and the foams are more stable. It should be recalled that protein adsorption times are much longer than those for surfactants. Actually, on Earth, foams stabilized by proteins (as well as particles) are difficult to generate but they are very stable afterwards [44]. Obviously, on the ISS, the drainage is reduced giving time to the proteins (particles) to reach the interface.

The ISS experiment demonstrated that all these wet foams were stable in zero-gravity conditions.

3.4 ISS future experiments: Foam coarsening

A foam coarsening project is presently supported by ESA and NASA. It is intended to achieve a more precise study of the coarsening phenomenon. Foams with very small bubble sizes will be prepared, and the coarsening will be studied using multiple light scattering techniques during several hours. The bubble growth laws have never been studied in the wet foam range, which is inaccessible on Earth. This study is however essential for the understanding of foam stability, as the time evolution of foams is largely controlled by bubble coarsening (the coalescence step being much more rapid in general) [25]. Another recent achievement is the demonstration that coarsening depends on the rheological properties of the surfactant layers at the bubbles surface [12], a fact unclear before.

The project will also provide new insight about the intermittent rearrangements of the packing structure induced by the diffusive gas exchange between neighbouring bubbles. In dry foams, multiple light scattering experiments [45] and simulations [46] have shown that these events are weakly correlated in time, and that they can be modelled statistically as a Poisson process. However, the elasticity of wet foams goes to zero at the jamming transition so that structural relaxation times become very large. This is expected to introduce correlations among successive rearrangements, leading to complex dynamics. Correlations between rearrangement events and their duration are not only relevant for coarsening, but they also play a key role in foam rheology [47]. Insight about rearrangement dynamics in wet foams will therefore help to understand the rheology or these materials close to the jamming transition. Moreover, in many applications, wet foams are made with dispersions containing hydrophilic solid particles. Very little is known so far about the coarsening dynamics of such three phase systems which are very unstable on Earth and the foam project will provide an opportunity to gain pioneering insight.

Recent variants of the multiple scattering of coherent light technique will be used to study the rate of bubble rearrangements that characterizes foam dynamics. This includes SVS: Speckle Visibility Spectroscopy and TRC: Time Resolved Correlation spectroscopy, that will be used to monitor the duration and temporal correlation of individual bubble rearrangement events [45]. Based on these experiments, an ISS module is being constructed and the flight is scheduled in 2016.

Let us finally mention that experiments on foams levitated by magnetic fields have been performed recently [7]. A transition from the regimes $R \sim t^{1/3}$ to $t^{1/2}$ has been observed upon changing the liquid volume fraction and was shown to be surprisingly sharp. This result needs to be confirmed.

4 Conclusions

It was shown that foams stable on Earth were also stable in microgravity: the foamability and foam lifetimes were generally increased. More strikingly, foams unstable on Earth become stable in microgravity: this is because gravity drainage is suppressed, capillary drainage is slowed down due to the quasi-spherical shape of the bubbles, coarsening is also slowed down because the films between bubbles remain thick, inhibiting coalescence as well. Antifoam agents are even ineffective due to the large film thickness and to the absence of buoyancy.

Capillary imbibition of foams has been studied in parabolic flights. A good agreement with theory and simulation was found at low liquid volume fraction, but discrepancies were evidenced for the wetter foams. Extensions of the theories are needed in order to model this process, which is important for a variety of other poroelastic materials such as plants and biological tissues for instance.

Coarsening of wet foams will be studied in a future ISS program. This study will be used to validate the recent results obtained on magnetically levitated foams especially close to the jamming transition where magnetic field inhomogeneities could generate forces between bubbles.

Microgravity experiments of wet foam rheology remain to be planned. Such experiments will allow to extend the results of Earth experiments close to the jamming transition.

The projects on foams in microgravity were financially supported by CNES, BISA, ESA and NASA, that are gratefully acknowledged. We are very grateful to Bernard Zappoli, Olivier Minster and Sebastien Vincent-Bonnieu for continuing support. We also benefited from numerous discussions and collaborations with the past and present members of the foam microgravity projects, Denis Weaire, Guy Verbist, Arnaud Saint Jalmes, Douglas Durian, Hervé Caps, Nicolas Vandewalle, Stefan Hutzler, Simon Cox, Sylvie Cohen-Addad, Reinhard Höhler, Olivier Pitois, Anne Laure Biance, Giles Delon, Emmanuelle Rio, Wiebke Drenckhan and Anniina Salonen.

References

1. D. Weaire, S. Hutzler (Editors), *The Physics of Foams* (Clarendon Press, Oxford, 1999).
2. P. Stevenson (Editor), *Foam Engineering: Fundamentals and Applications* (Wiley, 2012).
3. I. Cantat, S. Cohen-Addad, F. Elias, F. Graner, R. Höhler, O. Pitois, F. Rouyer, A. Saint-Jalmes, *Foams - Structure and Dynamics* (Oxford University Press, 2013).
4. E. Rio, W. Drenckhan, A. Salonen, D. Langevin, Adv. Colloid Interface Sci. **205**, 74 (2013).
5. S. Hutzler, D. Weaire, R. Crawford, Europhysics Lett. **41**, 461 (1998).
6. M.U. Vera, A. Saint-Jalmes, D.J. Durian, Phys. Rev. Lett. **84**, 3001 (2000).
7. N. Isert, G. Maret, C.M. Aegerter, Eur. Phys. J. E **36**, 1 (2013).
8. A.J. Liu, S.R. Nagel, in *Annual Review of Condensed Matter Physics*, Vol. **1**, edited by J.S. Langer (2010) pp. 347.
9. P. Taylor, Adv. Colloid Interface Sci. **75**, 107 (1998).
10. J. Lambert, I. Cantat, R. Delannay, R. Mokso, P. Cloetens, J.A. Glazier, F. Graner, Phys. Rev. Lett. **99**, 058304 (2007).
11. S. Hilgenfeldt, S.A. Koehler, H.A. Stone, Phys. Rev. Lett. **86**, 4704 (2001).
12. S. Tcholakova, Z. Mitrinova, K. Golemanov, N.D. Denkov, M. Vethamuthu, K.P. Ananthapadmanabhan, Langmuir **27**, 14807 (2011).
13. M. Le Merrer, S. Cohen-Addad, R. Höhler, Phys. Rev. E **88**, 022303 (2013).
14. A. Cervantes Martinez, E. Rio, G. Delon, A. Saint-Jalmes, D. Langevin, B.P. Binks, Soft Matter **4**, 1531 (2008).
15. M.B.J. Meinders, T. van Vliet, Adv. Colloid Interface Sci. **108**, 119 (2004).
16. A. Saint-Jalmes, Soft Matter **2**, 836 (2006).
17. S.A. Koehler, S. Hilgenfeldt, H.A. Stone, Langmuir **16**, 6327 (2000).
18. A. Saint-Jalmes, Y. Zhang, D. Langevin, Eur. Phys. J. E **15**, 53 (2004).
19. S.J. Cox, D. Weaire, S. Hutzler, J. Murphy, R. Phelan, G. Verbist, Proc. R. Soc. London, Series A-Math. Phys. Engin. Sci. **456**, 2441 (2000).
20. S.J. Neethling, H.T. Lee, J.J. Cilliers, J. Phys.: Condens. Matter **14**, 331 (2002).
21. E. Lorenceau, N. Louvet, F. Rouyer, O. Pitois, Eur. Phys. J. E **28**, 293 (2009).
22. F. Rouyer, O. Pitois, E. Lorenceau, N. Louvet, Phys. Fluids **22**, 043302 (2010).
23. J.M. Skotheim, L. Mahadevan, Science **308**, 1308 (2005).

24. S.J. Cox, G. Verbist, Microgravity Sci. Technol. **14**, 45 (2003).
25. D. Georgieva, A. Cagna, D. Langevin, Soft Matter **5**, 2063 (2009).
26. V. Carrier, A. Colin, Langmuir **19**, 4535 (2003).
27. A.L. Biance, A. Delbos, O. Pitois, Phys. Rev. Lett. **106**, 068301 (2011).
28. K. Khristov, D. Exerowa, G. Minkov, Colloids Surf. A-Physicochem. Engin. Aspects **210**, 159 (2002).
29. L. Saulnier, F. Restagno, J. Delacotte, D. Langevin, E. Rio, Langmuir **27**, 13406 (2011).
30. S.T. Tobin, A.J. Meagher, B. Bulfin, M. Mobius, S. Hutzler, Am. J. Phys. **79**, 819 (2011).
31. D. Langevin, E. Rio, in *Encyclopedia of Surface and Colloid and Science* edited by P. Somasundaran (Taylor and Francis, New York, 2012).
32. C. Monnereau, M. Vignes-Adler, B. Kronberg, J. Chim. Phys. Physico-Chim. Biolog. **96**, 958 (1999).
33. D.G.T. Barrett, S. Kelly, E.J. Daly, M.J. Dolan, W. Drenckhan, D. Weaire, S. Hutzler, Microgravity Sci. Technol. **20**, 17 (2008).
34. D.A. Noever, R.J. Cronise, Phys. Fluids **6**, 2493 (1994).
35. H. Caps, S.J. Cox, H. Decauwer, D. Weaire, N. Vandewalle, Colloids Surf. A-Physicochem. Engin. Aspects **261**, 131 (2005).
36. A. Saint-Jalmes, S. Marze, M. Safouane, D. Langevin, Microgravity Scie. Technol. **18**, 22 (2006).
37. A. Saint-Jalmes, S. Marze, H. Ritacco, D. Langevin, S. Bail, J. Dubail, L. Guingot, G. Roux, P. Sung, L. Tosini, Phys. Rev. Lett. **98**, 058303 (2007).
38. M. Anderson, B. Kronberg, C. Lockowandt, B. Prunet-Foch, M. Vignes-Adler, J. Phys. IV **11**, 227 (2001).
39. Y. Houltz, C. Lockowandt, P. Andersson, O. Janson, D. Langevin, A. Saint-Jalmes, S. Marze, M. Adler, O. Pitois, B. Kronberg, M. Andersson, in *17th ESA Symposium on European Rocket and Balloon Programmes and Related Research*, ESA Special Publications, Vol. **590** (2005), pp. 565.
40. D.A. Weitz, J.X. Zhu, D.J. Durian, H. Gang, D.J. Pine, Phys. Scr. **49B**, 610 (1993).
41. A. Saint-Jalmes, S.J. Cox, S. Marze, M. Safouane, D. Langevin, D. Weaire, Micrograv. Sci. Technol. **18**, 108 (2006).
42. N. Vandewalle, H. Caps, G. Delon, A. Saint-Jalmes, E. Rio, L. Saulnier, M. Adler, A.L. Biance, O. Pitois, S.C. Addad, R. Höhler, D. Weaire, S. Hutzler, D. Langevin, in *International Symposium on Physical Sciences in Space*, edited by A. Meyer, I. Egry, *J. Phys. Conf. Ser.*, Vol. **327** (2011), p. 01024.
43. V. Bergeron, P. Cooper, C. Fischer, J. GiermanskaKahn, D. Langevin, A. Pouchelon, Colloids Surf. A-Physicochem. Engin. Aspects **122**, 103 (1997).
44. B.S. Murray, R. Ettelaie, Curr. Opinion Colloid Interface Sci. **9**, 314 (2004).
45. A.S. Gittings, D.J. Durian, Phys. Rev. E **78**, 066313 (2008).
46. S. Vincent-Bonnieu, R.H. Höhler, S. Cohen-Addad, Europhys. Lett. **74**, 533 (2006).
47. J. Goyon, A. Colin, G. Ovarlez, A. Ajdari, L. Bocquet, Nature **454**, 84 (2008).