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Foam Stability in Microgravity

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Abstract. Within the context of the ESA FOAM project, we have studied the stability of aqueous and non-aqueous foams both on Earth and in microgravity. Foams are dispersions of gas into liquid or solid. On Earth, the lifetime of a foam is limited by the free drainage. By drainage, we are referring to the irreversible flow of liquid through the foam (leading to the accumulation of liquid at the foam bottom, and to a global liquid content decreases within the foam). When the liquid films become thinner, they eventually break, and the foam collapses. In microgravity, this process is no more present and foams containing large amounts of liquid can be studied for longer time. While the difference between foaming and not-foaming solutions is clear, the case of slightly-foaming solutions is more complicated. On Earth, such mixtures are observed to produce unstable froth for a couple of seconds. However, these latter solutions may produce foam in microgravity. We have studied both configurations for different solutions composed of common surfactant, proteins, anti-foaming agents or silicon oil. Surprising results have been obtained, emphasizing the role played by gravity on the foam stabilization process.

1. Introduction

Foams occur widely in nature and in important industrial processes and commercial applications [1]. Foams are made of closely packed gas bubbles in a liquid, typically water with an added surfactant. The liquid volume fraction \( \varphi \) may vary from less than one 1% (dry foam) to around 35% (wet foam). At low volume fractions, the bubbles are deformed into polyhedra. Most of the liquid is confined in the bubble edges called “Plateau borders”, connecting three films and which are themselves interconnected by “nodes”.

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 capillary-pressure gradient in the liquid and hence a vertical profile of liquid fraction is established. The addition of liquid to such a dry foam at the top results initially in a solitary wave with an approximately constant profile during its downward passage. Subsequently, a state of uniform drainage, with a constant volume fraction, is established. A sample undergoing such “forced” drainage can be used to study homogeneous wet foams, but only up to about \( \varphi = 20\% \) liquid fraction, beyond which various dynamic instabilities (primarily convection) occur. In the case of rheology, a very
interesting transition occurs at \( \varphi_c \approx 35\% \) where the foam changes from liquid-like (disconnected bubbles) to solid-like (finite shear modulus). This is the “jamming transition” also encountered in other assemblies of randomly packed objects, such as emulsions, sand, clays, etc. When \( \varphi > \varphi_c \approx 35\% \), the bubbles are spherical and move independently. Unfortunately, in the case of foams, the 20%-35\% range, which extends to the wet foam limit at which individual bubbles separate, remains inaccessible on Earth. This limits present experiments to stable dry foams, and indeed the idealized theoretical models are largely confined to the dry foam limit as well.

A zero gravity study of wet foam hydrodynamics allows one to overcome the limits imposed by various instabilities experienced under normal gravity [2, 3, 4]. This broader experimental characterization and corresponding insight will provide a scientifically valid alternative for the necessarily conservative empiricism currently employed to estimate the operational window and design for foam handling in industrial processes (such as gas/liquid contacting, flotation and pumping).

Microgravity experiments on foams represent therefore a big challenge for scientists. Within our collaboration, parabolic flight campaigns were conducted for testing foaming processes and more recently the FOAM-S mission took place on ISS for studying the stability of a foam. Some of the results of the latter experiment are detailed in the present paper. Unexpected behaviours will be emphasized.

2. FOAM-S mission

FOAM-S benefited from a flight opportunity to the ISS in 2009 during the stay of astronaut Frank DeWinne. The experiment consisted in shaking various solutions both on Earth and in the ISS in order to study the influence of gravity on foamability and stability of foams. For that purpose, a small rack, illustrated in Figure 1, has been specially built. It contains 12 cylindrical transparent cells (polycarbonate, height = 40 mm, inner diameter = 12 mm) containing a liquid solution. The liquid volume fraction is close to 30\% for all samples. This is our choice for studying foams near the critical liquid fraction \( \varphi_c \). Each cell contains also a spherical ceramic bead used for the foaming process. The diameter of the bead (11 mm) is slightly smaller than the tube inner diameter. When the rack is hand shaken by the astronaut during 10 seconds, the bead motion provides enough shear stress along the tube wall and foam is created within a few oscillations of the bead. After shaking, the tubes are placed in front of a light source and images are recorded thanks to a high resolution video recorder during 30 minutes.

A total of 60 closed cells containing various foaming solutions were embarked in 5 racks. Various samples have been tested. Among others, solutions were pure liquids, water surfactant mixtures including protein based agents. Antifoaming agents were also tested as well as for a chocolate foam. The samples were sent on ISS in 2009 (see Figure 2). Images have been returned to scientific teams during winter 2010. In order to compare to normal gravity conditions, ground based experiments have been performed using the same apparatus. First results are described in the next section.
Figure 1. Sketch of the experimental setup which consists in a small rack containing 12 samples in partially filled cylindrical cells. When the system is shaken by hand, the motion of a bead in each cell will provide enough shear stress along cylinder wall, and will therefore imply the mixing of air with the liquid. The stability of this fresh foam is recorded by a camera.

Figure 2. Astronaut Frank deWinne 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.

3. Experimental results
The pictures of the 60 samples recorded on the ISS have been collected and analyzed. Typical pictures of foam created in cylindrical cells are shown in Figure 3 for four different solutions both in zero gravity and Earth conditions: SDS, TTAB, casein and anti-foaming agent Rodorsil TF1 with SDS. One observes clear differences between 0g and 1g, as well as strong differences between samples. For example, the last sample of Figure 3 corresponds to an antifoam agent mixed in a SDS solution. The amount of foam created in micro-gravity seems more important
than observed on Earth. However, the foam is stable when the system is shaken in microgravity. This behavior was completely unexpected since anti-foaming agents are meant to avoid foam creation and stabilisation [5].

In order to measure the foamability of each solution [6], the amount of foam $\Phi$, ranging between 0% and 100%, created by shaking is measured on the pictures by image analysis. Foamability $\Phi$ is the volume fraction occupied by the foam only. It does neither consider the presence of the bead nor the presence of the remaining liquid. A rectangular zone is selected on the middle of a tube, in order to avoid the effect of the tube curvature. Such a rectangular zone is illustrated in Figure 3 by a black frame. A binarization threshold is applied to distinguish the foam from the rest of the tube: the foam appears in black. Then, the total area of the black region, representing the amount $\Phi$ of foam in the tube, is measured. The collected data are averaged over different runs. Table 1 summarizes our results. Among others, solutions shown in Figure 3 are denoted by a star "*". Note that in most cases, the foamability is almost two times larger on the ISS than on Earth. One exception is the solution of silica beads which was already very stable in Earth conditions [7]. A striking result is that a non-foaming solution on Earth exhibits a significant foam column in space! This behaviour was unexpected.

Figure 3. Snapshots of samples in respectively 0g and 1g after shaking: (top left) SDS 2g/L (top right) TTAB 0.34g/L, (bottom left) caseine-based 1g/L, (bottom right) anti-foaming agent Rodorsil with SDS 2g/L. The rectangular black frames drawn on the pictures illustrate the zones where $\Phi$ is measured.
Figure 4. Semi-log plot of the foam volume fraction $\Phi$ in the cell as a function of time $t$, for the solution of SDS 0.05 g/L (circle and solid circle respectively at 0g and 1g), the solution of SDS 2 g/L (triangle and solid triangle respectively at 0g and 1g), the solution of anti-foaming agent Rodorsil TF1 with SDS 2 g/L (square and solid square respectively at 0g and 1g).

Image analysis provides also relevant information on the foam stability when applied to image series. Figures 4, 5 and 6 present a semi-log plot of the foam fraction $\Phi$ in cell as a function of time (after hand shaking at time $t = 0$). Different dynamical behaviors should be emphasized. In 1g, a typical foam column collapses significantly within 30 seconds before starting a slow decrease for the remaining foam. The characteristic time scales for this decay depends mainly on the foaming agent since various physico-chemical processes are involved: drainage, film ruptures, bubble reorganisations. One can note a significative difference between foams made at 0g and 1g as already noted in Figure 3. In most cases, the quantity of foam is larger in 0g (the tubes are almost totally filled with foam made with the SDS). This is true for solutions under and above the CMC, and also for solutions with anti-foaming agent Rodorsil TF1. Moreover, these foams are showing a remarkable stability: the dynamics of $\Phi$ present a nearly flat curve in 0g. The amount $\Phi$ decreases rapidly in less than one minute before reaching a minimum. Whatever the observed solution on Earth, a characteristic time can be extracted, which is always around a few tens of seconds, whereas it is not the case in 0g. After ten seconds, the 0g foams are stabilized and no evolution is observed.
Figure 5. Semi-log plot of the foam volume fraction $\Phi$ in the cell as a function of time $t$, for the solution of TTAB $0.34g/L$ (circle and solid circle respectively at 0g and 1g) and for the solution of TTAB $0.024g/L$ (triangle and solid triangle respectively at 0g and 1g).

Figure 5 presents the results for TTAB solution above and below the CMC. The 0g foam shows a greater stability, and the quantity of foam is significatively more important than under gravity except for the solution of $0.34g/L$ of TTAB for which the quantities of foams are the same with and without gravity. After ten seconds, the 0g-foams are stabilized and do not evolve further. Figure 6 shows the evolution of foam for solution of casein. The foams made in the ISS present a great stability even if a weak decay can be observed during all the experiments and fill the tube four times more than foam produced on Earth. One should also note that sudden fluctuations are seen in one of the series around $t = 40$ s. This is due to a moving object or astronaut near the experiment modifying the lightning. Such an experimental artefact is hopefully very rare.

Figure 6. Semi-log plot of the foam volume fraction in the cell as a function of time, for the solution of casein $0.1g/L$ (circle and solid circle respectively at 0g and 1g) and for the solution of casein $1g/L$ (triangle and solid triangle respectively at 0g and 1g).
Table 1. List of selected samples and behaviours in 0g and 1g.

<table>
<thead>
<tr>
<th>solution</th>
<th>Φ(0g)</th>
<th>Φ(1g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDS 0.05g/L</td>
<td>0.569</td>
<td>0.295</td>
</tr>
<tr>
<td>SDS 2 g/L *</td>
<td>0.889</td>
<td>0.873</td>
</tr>
<tr>
<td>TF1 + SDS *</td>
<td>0.938</td>
<td>0.465</td>
</tr>
<tr>
<td>H2O/gly (30/70) +SDS</td>
<td>0.258</td>
<td>0.234</td>
</tr>
<tr>
<td>TTAB 0.024 g/L</td>
<td>0.71</td>
<td>0.026</td>
</tr>
<tr>
<td>TTAB 0.34 g/L *</td>
<td>0.697</td>
<td>0.351</td>
</tr>
<tr>
<td>Carboxymethylcellulose + TTAB</td>
<td>0.621</td>
<td>0.093</td>
</tr>
<tr>
<td>Tween 20 0.012 g/L</td>
<td>0.653</td>
<td>0.04</td>
</tr>
<tr>
<td>Tween 20 0.12 g/L</td>
<td>0.41</td>
<td>0.06</td>
</tr>
<tr>
<td>glass beads</td>
<td>0.42</td>
<td>0.435</td>
</tr>
<tr>
<td>Lysozyme</td>
<td>0.227</td>
<td>0.051</td>
</tr>
<tr>
<td>Lactoglobuline</td>
<td>0.4951</td>
<td>0.238</td>
</tr>
<tr>
<td>Casein 0.01g/L</td>
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<td>0.247</td>
</tr>
<tr>
<td>Casein 1g/L *</td>
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<td>0.267</td>
</tr>
<tr>
<td>Egg</td>
<td>0.519</td>
<td>0.327</td>
</tr>
<tr>
<td>Chocolate foam ingredients</td>
<td>0.627</td>
<td>0.055</td>
</tr>
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</table>

4. Discussion

Microgravity experiments allowed us to explore a new sort of foams with liquid fractions around ϕ = 30%. On Earth, such materials are unstable and most of the time not called foams but bubbly liquid. The liquid fraction is indeed so high that the bubbles can keep their spherical shape allowing to minimize their free energy. In contrary, at smaller liquid fractions, bubbles are connected to others bubbles and deformed: the surface of bubbles is flatten due to the gravity driven liquid flow through Plateau borders. The main process which controls the stability of a foam on Earth is the free drainage driven by gravity. Film thinning in the foam leads to a global decrease of the cell structure as observed in all data for 1g, even when the foaming agent is present. The thicker films indeed allow a faster gas transfer and, thus a faster coarsening. Moreover, they tend to reach a critical thickness at which they become unstable and burst. In 0 g, drainage is suppressed such that liquid films remains thick. Because ϕ = 30%, the foam remains wet. Bubble coalescence events are nevertheless seen, explaining a decrease of Φ on some plots. However, after some time, bubble motions become rare events such that the foam is more stable.

Note that the critical micellar concentration (CMC) is usually used to describe roughly the foamability. It is actually well known that a minimum concentration (around the CMC) is needed to create foam on Earth. Moreover, it has been observed that foamability is maximal around the CMC. This is actually due to surfactants remobilization. At large concentrations, the liquid indeed contains a large quantity of surfactants even after filling the surface. Hence, a small surface gradient is rapidly compensated by surfactants exchanges with the bulk and the surface elasticity is drastically decreased leading to smaller stability [10, 11]. As a result, on Earth, low concentration solutions do not foam or lead to unstable foams. Note that the considerations concerning surface rheology are still valid in the ISS but the foamability is also good for small concentrations. Then, it seems that in 0g, the CMC is no more a good order of magnitude for the frontier between stable and unstable foams. Indeed, surface rheology becomes important as soon as the films become very thin and can burst [8]. Concerning the results different on Earth and in space, there are also proteins which behave differently. In this case, it is worth noticing that they need quite a long time to reach the interface [10]. Actually, on Earth, foams
stabilized by proteins (as well as particles) are very stable once generated but are very difficult to generate [11]. Obviously, on the ISS, the drainage is reduced giving time to the proteins to reach the interface. The various physical ingredients behind this unexpected stability have to be identified. We believe that the liquid fraction is an important parameter as tested in earlier parabolic flights.

5. Conclusion
From the FOAM-S experiment, we discovered the possibility to create super stable aqueous foams in zero gravity conditions. Even on Earth, coarsening and film ruptures are always present for a solution with foaming agents. In zero gravity, the foam evolves certainly but the amount of foam Φ does not appear to change significantly. Surprisingly, antifoaming agents have a reduced effect in microgravity, and this particular foam appears to be stable. This result raises new fundamental questions that should be investigated in future works.

In the FOAM-S experiment, cells have been filled with the same quantity of liquid (around 30% close to the rigidity loss transition). New experiments are needed to study the effect of this parameter on the amount of generated foam.

Acknowledgements
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References