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Foam imbibition in microgravity

An experimental study

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Abstract. We report an experimental study of aqueous foam imbibition in microgravity with strict mass conservation. The foam is in a Hele-Shaw cell. The bubble edge width ℓ is measured by image analysis. The penetration of the liquid in the foam, the foam imbibition, the foam inflation, and the rigidity loss are shown all to obey strict diffusion processes. The motion of bubbles needed for the foam inflation is a slow two-dimensional process with respect to the one-dimensional capillary rise of liquid. The foam is found to imbibes faster than it inflates.

PACS. 82.70.Rr Aerosols and foams – 83.80.Iz Emulsions and foams

1 Introduction

Foams are paradigms of disordered cellular systems. Bubbles composing foams are indeed characterized by a wide variety of side numbers and face areas [1]. Among the physical properties of interest, one can cite the topological rearrangements [2–4], the cascades of popping bubbles [5,6], the rigidity loss transition [7], etc.

In aqueous foams, a fundamental process is the free drainage [8] which is due to the competition between gravity forces, viscous forces and capillary pressure in channels separating adjacent bubbles. The drainage effects imply that the top of the foam becomes dry while the bottom of the foam remains wet. The dry foam is composed of polyhedral bubbles meeting on thin edges, while the wet foam is composed of spherical bubbles which can sometimes move freely [7]. In the absence of gravity ($g = 0$), only capillary and viscous forces act [9].

Koehler *et al.* [10] have numerically and theoretically studied these processes. They distinguished zero gravity ($g = 0$) and free drainage ($g \neq 0$) cases. They concluded that in a free drainage process the foam evolves towards a steady-state, *i.e.* a wet foam and a dry foam region. Even though the results for $g \neq 0$ are those expected and have been verified by Koehler *et al.* in [11], the $g = 0$ case obviously needs to be experimentally studied. The present letter deals with such a case.

An experimental study of foam wetting in microgravity is necessarily raising plenty of theoretical and practical questions [9]. The aims of the present work are (i) to describe this experiment, and (ii) to study the dynamical evolution of the foam liquid fraction in zero-gravity conditions.

2 Experiments

Microgravity experiments were held during a parabolic flight campaign organized by the European Space Agency (ESA). About 30 parabolas have been dedicated to this experiment.

Parabolic flights allow for 20 s in microgravity with an average acceleration less than $a = 0g \pm 0.05g$. Each parabola is composed of three parts. The *pull up* which is a hypergravity phase ($a \simeq 2g$), when the plane is inclined at 37°. The *microgravity* is established at the top of the parabolic trajectory. During the *pull out*, *i.e.* the end part of the parabola, the vertical acceleration is again $a \simeq 2g$.

The experimental procedure was the following. A soap-water mixture was inserted in a vertical Hele-Shaw (HS) cell. The commercial soap was mainly composed of dodecylsulfate (surface tension $\sigma = 0.03$ N/m, viscosity $\eta = 0.001\ \mathrm{kg\,m^{-1}\,s^{-1}}$). The HS cells were closed parallelipedic vessels constituted of 2 pieces of Plexiglas (20×20 cm^2) distant of 0.2 cm from each other. This distance has been judiciously chosen in order to form only one layer of bubbles, *i.e.* a two-dimensional foam. Before each parabola, the HS cell was vigorously shaken for creating the foam. The HS cell was placed vertically in a cage fixed to the plane for enhancing the drainage before the microgravity phase. During the flights, a CCD camera recorded the evolution of the foam. Image treatment and analysis have been later performed in order to characterize the bubble edges and the liquid motion in the foam.

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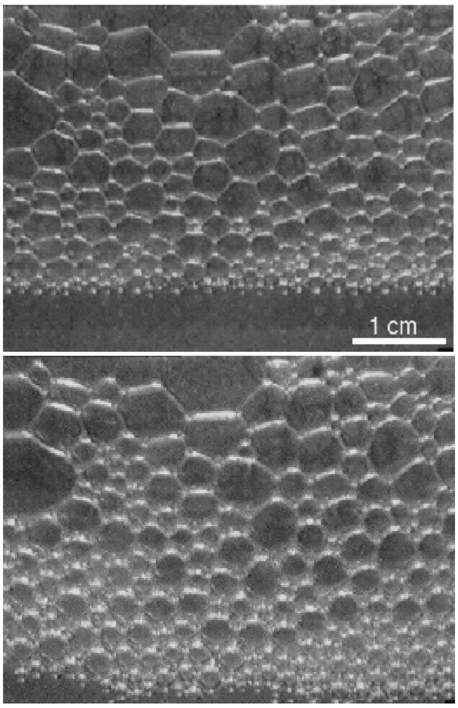

Fig. 1. (top) Image of the foam during the hypergravity phase. The bottom is composed of small 'wet' bubbles while the top is composed of large 'dry' bubbles. (bottom) The same foam after 10 seconds of microgravity. All bubbles become spherical and bubble walls thicken.

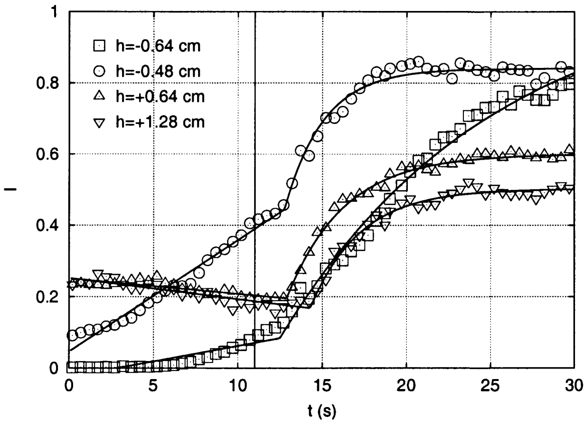

Fig. 2. Typical evolution of the bubble edges width ℓ as a function of time t for 4 different vertical positions h. Fits using equation (1) are shown. The vertical line corresponds to the beginning of the microgravity phase, $t_m = 11$ s in this example. A break of $\ell(t)$ is clearly observed at $t_0 > t_m$.

3 Results

Figure 1 presents the foam during the hyper- and microgravity phases respectively. During the hypergravity phase (top picture in Fig. 1), the bottom of the foam above the liquid is composed of small "wet" bubbles while the top is composed of large polygonal "dry" bubbles. Some bubble motion due to the plane vibrations is seen at the bottom of the foam. The moves concern the small bubbles only.

When the microgravity is established, the situation changes drastically: the liquid invades the foam from below such that the average thickness of all bubble edges increases as seen in the lowest part of Figure 1. The bubbles become more rounded and the rigidity of the foam is weakened, allowing bubbles to slip on others and to move freely due to the airplane vibrations. It should be noticed that small bubbles become rounded first. The smallest ones are also dragged by the rising liquid towards the top of the foam (see the central part of the bottom picture). Moreover, the front separating wet and dry phases is well seen to propagate from bottom to top on the video records. Because of the liquid invasion in the foam, the distance between adjacent bubbles grows and some bubbles move down to the bottom of the HS cell. In other words, the foam invades the liquid phase; *the foam inflates.* When the microgravity phase ends, an acceleration of about $2g$ leads to a fast and global drainage of the foam. The foam returns to the initially dry situation quite rapidly, as in the top picture.

In order to quantify the wetting of the foam, the thickness of the bubble edges has been measured by image analysis. The video recording of each parabola has been decomposed in a series of successive images at a rate of 10 frames per second. Each image has been numerically modified for enhancing the bubble edges (bright parts of Fig. 1). The image resolution is about 10^{-2} cm, what is sufficient to measure accurately the mean bubble edge width since those edges are typically 1 mm wide. On any horizontal line situated at a vertical position h on the black and white images, the fraction of bubble edges ℓ is measured. The parameter ℓ is given in units of the image width such that $0 < \ell < 1$. A large value of ℓ corresponds to a wet foam, while a small value of ℓ is the signature of a dry foam. One should note that the origin of h has been judiciously chosen such that the bottom of the foam corresponds to $h = 0$ at the end of the pull-up. We have analyzed more than 2500 images taken during 30 parabolas.

Figure 2 presents the typical evolution of the bubble edges width ℓ as a function of time t for 4 different vertical positions h. Each dot corresponds to an average over 5 measurements, *i.e.* 5 parabolas. Only the pull-up phase and the microgravity phase are illustrated on Figure 2. The microgravity startup time t_m is emphasized by the vertical line. *All* curves exhibit a break at some time $t_0 > t_m$.

The features of ℓ should be interpreted differently for $h > 0$ and $h < 0$. Consider first the case $h > 0$, *e.g.* $h = 0.64$ cm and $h = 1.28$ cm. During the hypergravity phase, the foam is rigid and bubble edges are very thin. A small value of ℓ (≈ 0.2) is seen in Figure 2 to be slightly decreasing with time, due to the acceleration phase. After the microgravity phase begins, a rapid growth of ℓ is observed. This corresponds to the imbibition of the foam, more precisely the invasion of the liquid along bubble edges. The liquid fraction saturates after some time.

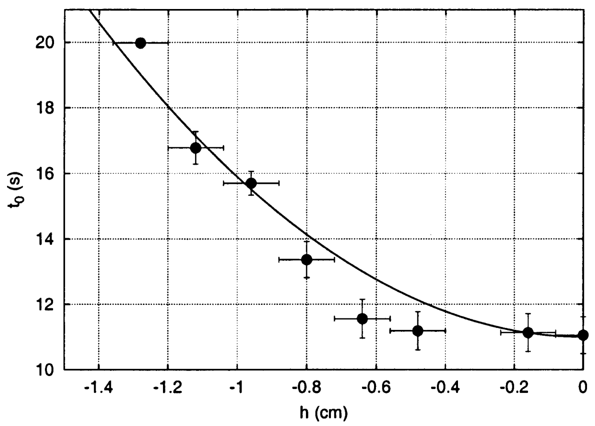

Fig. 3. The time t_0 needed for the liquid to reach a height $h > 0$. A fit using equation (2) is shown.

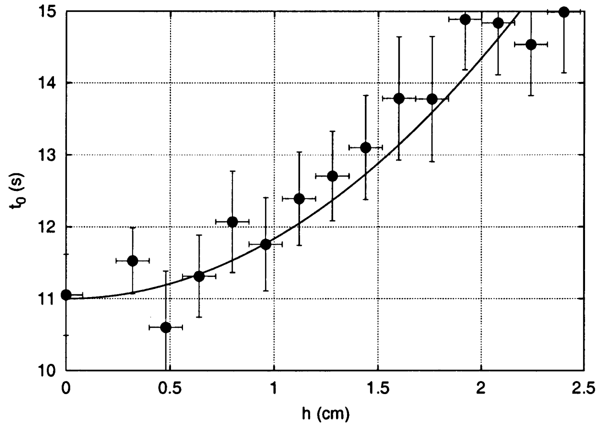

Fig. 4. The time t_0 needed for the bubbles to fall down to a position $h < 0$. A fit using equation (5) is shown.

The dynamics of liquid invasion can thus be extracted from $h > 0$ measurements.

Consider now the $h < 0$ curves of Figure 2, *e.g.* $h = -0.48$ cm and $h = -0.64$ cm. During the hypergravity phase, only a few round bubbles are moving at the bottom of the foam due to plane vibrations. This implies $\ell \neq 0$ on average even for $h < 0$. As the microgravity phase begins at t_m, the liquid invades the foam which "inflates" since the bubbles are allowed to move towards the bottom of the HS. For $t > t_m$, a rapid growth of ℓ is observed, which corresponds to the invasion of the foam into the fluid phase. The bubble edges width ℓ is seen to saturate about 10 seconds after t_m. Using the $h < 0$ data, we can thus study the invasion of the foam into the fluid phase, namely the foam inflation dynamics.

We thus see that the evolution of the inter bubble channel width ℓ is a relevant parameter in order to characterize the foam evolution. Considering that ℓ saturates during the microgravity phase, we have assumed the empirical law

$$\ell = \begin{cases} a + b\,(t - t_0) & \text{if } t < t_0 \\ a + c\,(1 - \exp\left(-(t - t_0)/\tau\right)) & \text{elsewhere} \end{cases} \tag{1}$$

where a, b, c, τ and t_0 are 5 free fitting parameters at each height h; a, b and c being geometrical parameters. The relevant physical parameters for our study are: the time t_0 at which the bubble edges become to grow for a given height h and the characteristic time τ of wetting. Both parameters will be examined separately. Fits are shown in Figure 2.

The parameter t_0 is different from t_m since there is a time delay needed for the liquid to reach the vertical position $h > 0$ or the foam to invade the liquid phase for $h < 0$. Figure 3 presents the time t_0 needed to the liquid to reach the vertical position $h > 0$. We have fitted the results by a general power law, and have found a power exponent close to 2. Thus, the wet front position behaves like

$$h = \sqrt{D_w(t_0 - t_m)}\ . \tag{2}$$

The liquid rise (imbibition) in the initially dry foam is clearly a diffusive process with a coefficient $D_w = 1.19 \pm 0.07$ cm^2 s^{-1} for commercial soaps. Within the formalism of the drainage equation [11], in the case of node dominated drainage in the absence of gravity, the imbibition of the foam is found to obey a diffusion law. The diffusivity D reads

$$D = \frac{\sigma}{2\eta} K \delta\, L, \tag{3}$$

where L is the bubble edge length, K is some permeability factor depending on the foam, δ is a pre-factor depending on the bubble edges. In [11] Koelher *et al.* estimate $K = 0.002$ and $\delta = 0.41$. Considering the surface tension σ and viscosity η values of our experiment, the diffusivity D is expected to be $D = 1.2\ L$ cm^2 s^{-1}, with $L \simeq 0.6$ cm here. The theoretical value is thus of same order of magnitude as that we measured, despite the fact that some theory hypotheses [11] are not encountered here. Indeed, (i) the monodisperse approximation is obviously not encountered, (ii) a continuum approximation is not trivially obeyed (for example, the size of our samples is not much larger than the bubble size), (iii) the channel width fluctuations are usually not much larger than the bubble size. Nevertheless, equation (3) may give us an idea on how the diffusivity depends on the geometrical parameters of the foam and on the physical properties of the fluid. Let us write

$$D = U^\star L, \tag{4}$$

where $U^\star$ is a characteristic imbibition velocity depending on the permeability K, on the value of δ, and the fluid properties η and σ. For the foam imbibition, we estimate $U^\star_w \simeq 2$ cm s^{-1} what is in good agreement with direct observations.

In addition to the liquid propagation, invasion of the foam into the fluid phase – what we call "foam inflation" – is observed. The dynamics of this process is captured by the parameter t_0 for $h < 0$ and is illustrated in Figure 4. The foam *inflation* behaves like

$$-h = \sqrt{D_i(t_0 - t_m)}\ . \tag{5}$$

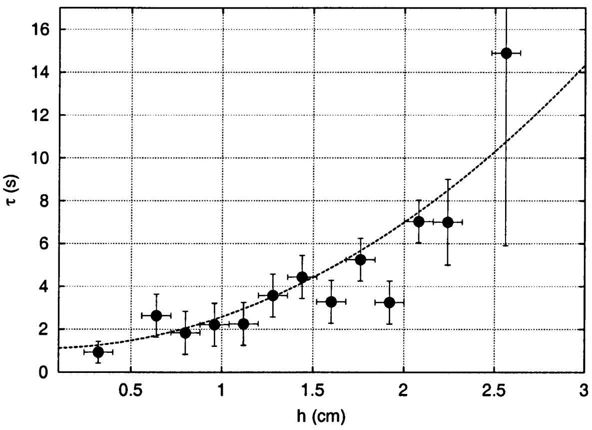

Fig. 5. Characteristic rigidity loss time τ as a function of the height $h > 0$. The fit uses equation (7).

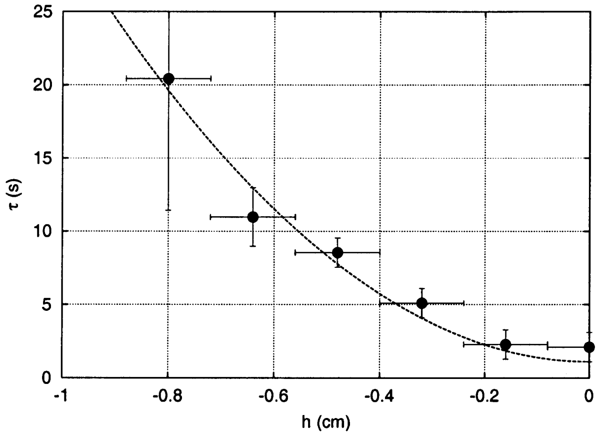

Fig. 6. Characteristic horizontal diffusion time τ as a function of the height $h < 0$. Fit using equation (8) is illustrated.

The foam inflation is also a diffusive process with a coefficient $D_i = 0.21 \pm 0.02$ cm^2 s here. The characteristic speed of this process is $U_i^\star = 0.35$ cm s^{-1}. It is readily observed that $D_w > D_i$. The motion of bubbles needed for the foam inflation is a slow *two-dimensional* process with respect to the *one-dimensional* capillary rise of liquid. In short, *the foam wets faster than it inflates.*

An interpretation of the difference between D_w and D_i comes from the incompressibility of both air and liquid. The flux of water rising in the bubble edges must be equal to the flux of air invading the fluid phase by the way of bubbles. In 2D, this relation reads

$$\ell_r\, U_w^\star = L\, U_i^\star. \tag{6}$$

The bubble edge width ℓ_r is typically 1 mm while the bubble edge length L is nearly 0.6 cm. The bubble edge length-width ratio is thus typically $L/\ell_r = 6$ and is so equal to the ratio $U_w^\star/U_i^\star$. Thus, the characteristics speed of the imbibition process is 6 times larger than the characteristic speed of the foam inflation process.

Measurements of the time t_0 at which the bubble edges become to grow allowed us to characterize the imbibition of the foam as well as the invasion of the foam into the fluid. However, the study of the dynamical parameter τ of the bubble edge growth may give us some informations on the foam properties. Once adjacent bubbles are imbibed by the rising liquid, they start to move apart because the bubble separation increases. This process tends to decrease the foam rigidity. Eventually, the bubbles can move independently. The rigidity loss is closely related to the imbibition of the foam: the faster rises the front of water, the faster is this process. Informations on the dynamics of rigidity loss can thus be captured by the parameter τ for $h > 0$. In Figure 5, we report the measurement of τ as a function of the vertical position $h > 0$. We have found that a quadratic expression fits the data. One has

$$h = \sqrt{D_r \tau}\,, \tag{7}$$

meaning that the bubbles take a long time to separate at the bottom of the HS cell. A diffusive law is found, with a diffusivity $D_r = 0.68$ cm^2 s^{-1}. Figure 6 shows the measurement of τ as a function of the vertical position $h < 0$. This represents the horizontal motion of bubbles under the initial water-foam interface once the foam inflates. Indeed, a rapid saturation of the bubble edges width means that a "steady-state" is shortly reached. This process also follow a diffusion law

$$-h = \sqrt{D_m \tau}\,, \tag{8}$$

with a small coefficient D_m. The motion amplitude of the bubbles in a wet phase is indeed quite small. In Table 1, the values of the various diffusion coefficients encountered in the present study are given.

Table 1. The different diffusion coefficients measured in our experiment. The liquid rise (wetting) is characterized by D_w. The foam inflation is characterized by D_i. The rigidity loss is characterized by D_r. The motion of individual bubbles in the wet phase is characterized by D_m.

$h > 0$	t_0	$D_w = 1.19 \pm 0.07$ cm^2 s^{-1}
	τ	$D_r = 0.68 \pm 0.07$ cm^2 s^{-1}
$h < 0$	t_0	$D_i = 0.21 \pm 0.02$ cm^2 s^{-1}
	τ	$D_m = 0.035 \pm 0.002$ cm^2 s^{-1}

Integrating the so-called drainage equation (for $g = 0$), Koehler *et al.* [11] predicted a diffusive behavior for the volume fraction of liquid in the foam. The qualitative agreement between this theory and our experiment is astounding in spite the crude approximations (continuity for example) made in this theory.

As mentioned before, the bubble edge evolution should depend on the physical parameters (surface tension, viscosity, bubble size...). The values of the D_w, D_r, D_i and D_m are not universal. The diffusive motion is thus the key process during foam imbibition, foam inflation and rigidity loss.

In summary, our experiments show that in microgravity, foam imbibition obeys diffusive processes. This behavior was predicted by Koehler *et al.* [11] within the drainage equation formalism. As far as we know, it is the first time that this dynamical characteristics is obtained experimentally in microgravity conditions. Moreover, we have noted that the foam imbibition ("foam wetting") can be viewed in terms of capillary rise, bubble motion and rigidity loss. All these processes obeying diffusive behaviors.

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