Diffusive foam wetting process in microgravity

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We report the experimental study of aqueous foam wetting in microgravity. The liquid fraction $\ell$ along the bubble edges is measured and is found to be a relevant dynamical parameter during the capillary process. The penetration of the liquid in the foam, the foam inflation, and the rigidity loss are shown all to obey strict diffusion processes.

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Foams are paradigms of disordered cellular systems. Bubbles composing foams are indeed characterized by a wide variety of side numbers and faces areas \([1]\). The complexity of the foam can only be described by statistical averages. Among the physical properties of interest, one can cite the topological rearrangements \([2]\), the cascades of popping bubbles \([3,4]\), the rigidity loss transition \([5]\), etc...

In aqueous foams, a fundamental process is the drainage \([3]\) which is due to the competition between gravity forces and the capillary pressure in channels separating adjacent bubbles. The drainage-capillary effects imply that the top of the foam becomes dry while the bottom of the foam remains wet. A dry foam is composed of polyhedral bubbles meeting on thin edges, while wet foams are composed of spherical bubbles which can sometimes move freely \([6]\).

We report here the experimental study of foam wetting in microgravity. The aims of the present letter are (i) to report the behavior of a foam in microgravity and, (ii) to characterize the wetting of such a foam. Physical mechanisms will be emphasized and characterized.

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 ($a \approx 2g$), when the plane is inclined at $37^\circ$. 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 $a \approx 2g$.

The experimental procedure was the following. A soap-water mixture was inserted in a vertical Hele-Shaw (HS) cell. The soap was mainly composed of dodecylsulfate. The HS cells were closed parallelepipedic vessels constituted of 2 pieces of plexiglass ($20 \times 20 \text{ cm}^2$) 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.

Figure 1 presents the foam during the hyper- and micro-gravity phases respectively. During the hypergravity phase, the bottom of the foam above the liquid is composed of small “wet” bubbles while the top is composed of large polygonal “dry” bubbles as seen on the top picture of Figure 1. 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 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 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 record 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 Figure 1). On any horizontal line situated at a vertical position $h$ on the images, the fraction of bubble edges $\ell$ is measured. This corresponds to the liquid fraction at that position. The parameter $\ell$ is given in units of the image width such that $0 < \ell < 1$. A large value of $\ell$ corresponds to a wet foam, while a small value of $\ell$ 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.

![Image of foam](bottom) 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.

Figure 1 presents the typical evolution of the liquid fraction \( \ell \) 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 beginning of the microgravity phase at time \( t_m \) is emphasized by a vertical line. All curves exhibit a break of \( \ell(t) \) at \( t_0 > t_m \).

The features of \( \ell \) should be interpreted differently for \( h > 0 \) and \( h < 0 \). Consider first the case \( h > 0 \), e.g. \( h = 0.64 \text{ cm} \) and \( h = 1.28 \text{ cm} \). During the hypergravity phase, the foam is rigid and bubble edges are very thin. A small value of \( \ell \) (\( \approx 0.2 \)) 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 \( \ell \) is observed. This corresponds to the wetting of the foam, more precisely the invasion of the liquid along bubble edges. The liquid fraction saturates after some time. The dynamics of liquid invasion can thus be extracted from \( h > 0 \) measurements.

Consider now the \( h < 0 \) curves of Figure 2, e.g. \( h = -0.48 \text{ cm} \) and \( h = -0.64 \text{ cm} \). 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. A rapid growth of \( \ell \) is observed for \( t > t_m \) which corresponds to the foam inflation. The liquid fraction \( \ell \) is seen to saturate about 10 seconds after \( t_m \). Using the \( h < 0 \) data, we can thus study the foam inflation dynamics.

We thus see that the evolution of the inter bubble liquid fraction \( \ell \) is a relevant parameter in order to characterize the foam evolution. Considering that \( \ell \) saturates during the microgravity phase, we have assumed the empirical law

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

where \( a, b, c, \tau \) and \( t_0 \) are 5 free fitting parameters at each height \( h \). The relevant physical parameters for our study are: the time \( t_0 \) at which the liquid fraction becomes to grow for a given height \( h \) and the characteristic time \( \tau \) of wetting. Both parameters will be examined separately. Fits are shown in Figure 2.

The parameter \( t_0 \) can be different from \( t_m \) since there is a time delay needed for the liquid to reach the vertical position \( h > 0 \) or the foam inflation for \( h < 0 \). Figure 2 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

![Graph of liquid fraction vs time](below) Typical evolution of the liquid fraction \( \ell \) as a function of time \( t \) for 4 different vertical positions \( h \). Fits using Eq. (1) are shown. The vertical line corresponds to the beginning of the microgravity phase, \( t_m = 11 \text{ s} \) in this example. A break of \( \ell(t) \) is clearly observed at \( t_0 > t_m \).
\[ h = \sqrt{D_w(t_0 - t_m)} \] (2)

The liquid rise (wetting) in the initially dry foam is clearly a diffusive process with a coefficient \( D_w = 1.19 \pm 0.07 \text{ cm}^2/\text{s} \). In addition to the liquid propagation, the foam inflation has been 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

\[ -h = \sqrt{D_i(t_0 - t_m)} \] (3)

The foam inflation is also a diffusive process with a coefficient \( D_i = 0.21 \pm 0.02 \text{ cm}^2/\text{s} \). By comparing both coefficients, one observes that \( D_w > D_i \). Indeed, 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.

Once adjacent bubbles are wetted by the rising liquid, they start to move apart because the bubble separation increases. This process lasts until the foam rigidity is lost. Then, the bubbles can move independently. The rigidity loss can be captured by the parameter \( \tau \) for \( h > 0 \). In Figure 5, we report the measurement of \( \tau \) as a function of the vertical position \( h > 0 \). We have found that a quadratic expression fits the data. One has

\[ h = \sqrt{D_r \tau} \] (4)

meaning that the bubbles take a long time to separate at the bottom of the HS cell. Again, a diffusive behavior is found with a coefficient \( D_r \). The kinetics of rigidity loss is close to the one of wetting but twice lower. Figure 6 shows the measurement of \( \tau \) as a function of the vertical position \( h < 0 \). This represents the horizontal motion of bubbles at the bottom of the HS cells once the foam inflates. This is also a diffusion process

\[ -h = \sqrt{D_m \tau} \] (5)

with a small coefficient \( D_m \). Indeed, the motion of bubbles in a wet phase is quite small.
FIG. 6. Characteristic horizontal diffusion time $\tau$ as a function of the height $h < 0$. Fit using Eq.(5) is also illustrated.

In the case of drainage under gravity, an equation has been proposed by Verbist and coworkers [6] for describing a Poiseuille flow along bubble edges. The drainage equation does not apply here because of the microgravity ($g \approx 0$) and the foam inflation we observed. Except for capillary forces at the beginning of the process, (i) no driving force pushes the liquid in our case, and (ii) one sees (after some time) the individual motion of bubbles in a liquid foam. Diffusive motion is thus the key process during foam wetting, foam inflation and rigidity loss. The “square root of time” behaviors that we observe confirm this hypothesis. Table I lists the values of the various diffusion coefficients encountered in the present study.

| $h > 0$ | $D_w = 1.19 \pm 0.07 \text{ cm}^2/\text{s}$ | $D_r = 0.68 \pm 0.07 \text{ cm}^2/\text{s}$ |
| $h < 0$ | $D_i = 0.21 \pm 0.02 \text{ cm}^2/\text{s}$ | $D_m = 0.035 \pm 0.002 \text{ cm}^2/\text{s}$ |

TABLE I. 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 $D_m$.

In summary, we have studied experimentally the dynamics of foam wetting in microgravity. We have confirmed that the liquid invasion behaves clearly as a diffusive process.

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