PHYSICAL REVIEW E, VOLUME 64, 021507

Cascades of popping bubbles along air/foam interfaces

N. Vandewalle and J. F. Lentz
GRASP, Institut de Physique B5, Université de Liège, B-4000 Liège, Belgium

(Received 29 December 2000; published 19 July 2001)

We report image analysis of popping bubbles during the collapsing of two-dimensional (2D) and 3D aqueous foams. Although temporal and spatial correlations between successive popping bubbles within avalanches are emphasized, the breaking of a soap film at the air/foam interface seems to be independent of (i) the topology, (ii) the local curvature, and (iii) the size of the popping bubble. Possible mechanisms for cascades of pops are proposed and discussed.

DOI: 10.1103/PhysRevE.64.021507 PACS number(s): 82.70.Rr, 83.80.Hj

I. INTRODUCTION

Foams are paradigmatic systems of disordered and heterogeneous materials [1]. Indeed, polyhedral bubbles composing foams are characterized by a wide variety of side numbers and face areas. In aqueous foams, a fundamental process is the drainage [2] which is due to the competition between gravity forces and the capillary pressure in channels and plateau borders. As a consequence, the top of the foam tends to be dry while the bottom of the foam remains wet. The drainage implies that the film at the air/foam interface becomes thin and fragile. Frailty of the bubbles at the top of the foam leads to film breaking (bubble popping) and consequently leads to a macroscopic collapse of the foam as usually observed in beer and soap froths.

Imposing a thermal perturbation, Burnett *et al.* [3] reported "cascades" of film ruptures in soap solutions. The dynamics of those cascades is characterized by scaling laws. In a recent work [4], we reported acoustic measurements of popping bubbles in freely collapsing foams. We put into evidence the existence of temporal correlations for successive pops. Each pop may provoke the cracking of neighboring bubbles in some sort of avalanching process or cascade. Also, we measured the acoustic energy release for each pop. A broad distribution of energy dissipation has been discovered [4]. Our acoustic measurements suggest that a broad distribution of bubble breaking at the air/foam interface exists. This result is in contrast with the widely accepted and intuitive argument that only large bubbles are fragile and explode at the air/foam interface. On the contrary, our acoustic experiment has demonstrated that small bubbles also explode [4].

Because a possible existence of a critical size for film rupture is still unclear [4,5], and because our acoustic study should be confronted to other experimental investigations, we report here image recording of the air/foam interface. Image analysis allows us to visualize the topological rearrangements produced by popping bubbles. Fundamental processes at the surface of collapsing foams are revealed and discussed.

II. EXPERIMENTAL INVESTIGATIONS

Two different types of aqueous foam systems have been investigated: (i) three-dimensional (3D) foams in a cyclindric vessel, and (ii) 2D foams in a vertical Hele Shaw cell. Those different geometries will allow us to investigate both surface and bulk rearrangements due to bubble pops.

A. 3D foams in cyclindric vessels

In the first series of experiments, foams have been created by blowing air at the base of a water-soap mixture in a cylindric vessel. The diameter of the container is 20 cm. Commercial soaps (mainly dodecylsulfate) have been used. Looking at the foam along the vertical axis, polyhedral bubbles (typical diameter $d=5$ mm) are observed near the air/foam interface while spherical bubbles (typical diameter $d=2$ mm) are seen at the water/foam interface. The size difference observed for bubbles located, respectively, at the bottom and the top of the foam layer should be attributed to a buoyancy effect [6]. The thickness of the foam layer can be controlled such that the foam can be considered as dry in the region of our interests, i.e., at the air/foam interface. Then, the foam is left to collapse freely without any perturbation. A charge-coupled device (CCD) camera has been placed just above the crackling foam. Series of topview images of the air/foam interface have been recorded. Figure 1 (left) presents a typical top view of this interface. Each bubble at the surface presents a very thin and curved top face. Inside the foam, bubbles are polyhedra.

Bubble pops occur mainly at the air/foam interface. They cannot be captured by our video equipment. Indeed, such an event has a typical duration of about 1 ms as demonstrated in our previous acoustic measurements [4]. Nevertheless, bubble pops can be put into evidence by substracting succes-

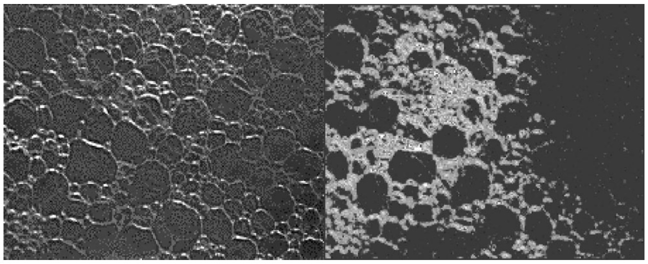

FIG. 1. (left) Picture of the air/foam interface taken by the CCD camera. (right) The difference between two successive images reveals a single popping event that provokes topological rearrangements along the air/foam interface.

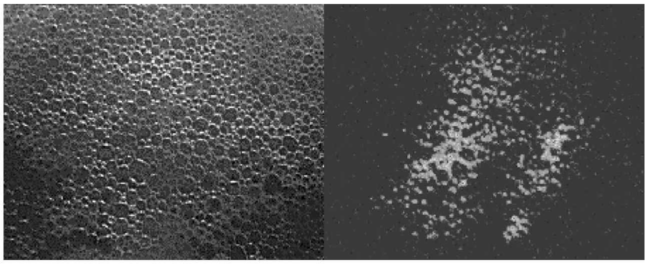

FIG. 2. (left) Picture of the air/foam interface taken by the CCD camera. (right) The difference betwen two successive images reveals a double popping event.

sive images of the air/foam interface. The substraction of successive images reveals also the subsequent topological rearrangements due to the pops. This information was not extracted in [4] since acoustic measurements are insensitive to topological rearrangements. Figure 1 (right) presents a typical pattern due to a popping event. One can observe that topological rearrangements (mainly edge and vertex displacements) spread over long distances along the air/foam interface. Typically, topological rearrangements can affect bubbles that are at a distance up to 10 bubble diameters from the rupture point. Only rearrangements along the air/foam interface can be investigated with this experiment. Bulk rearrangements will be discussed in the following section.

The sampling rate for the image series is 25 Hz. During the time intervals of 1/25 second separating the capture of two images, double pops may occur. In fact, those double pop events are not so rare. They correspond to pops occuring within a cascade. Figure 2 reveals such a situation for which two pops are seen (two bright regions). In our previous work [4], we put into evidence temporal correlations for successive pops. Herein, both pops seem to be correlated in space. Indeed, the topological rearrangements associated with both pops are connected. We have noticed that the connection of rearrangements takes always place on double pop pictures. This gives a complementary view of the phenomenon.

B. 2D foams in vertical Hele Shaw cells

Aqueous foams have also been investigated in vertical Hele-Shaw (HS) cells that constrain the foam in quasi-two dimensions. Typically, we used HS cells with a volume of $200\times200\times3\ \text{mm}^3$.

By image analysis and using a thresholding method, the edges of the bubbles can be selected on the pictures. Then, the bubbles are counted and their respective topological indices n, i.e., their respective numbers of neighbors, are measured. We have distinguished bubbles in contact with the air/foam interface and those that are in the bulk of the foam.

The evolution of 2D dry foam is slow and driven by geometrical constraints like the topological indices n of bubbles. Indeed, the area A_n of a bidimensionnal bubble evolves according to the Von Neumann's law

$$\frac{dA_n}{dt}=k(n-6). \tag{1}$$

In addition, many topological rearrangements such as the cell side switching ($T1$) or the vertex disappearance ($T2$) also take place [1]. The combination of bubble area growth/decay and topological rearrangements induces a complex dynamics in which subtle correlations are found as e.g. described by the so-called Aboav-Weaire law [1] or more complex structures [7].

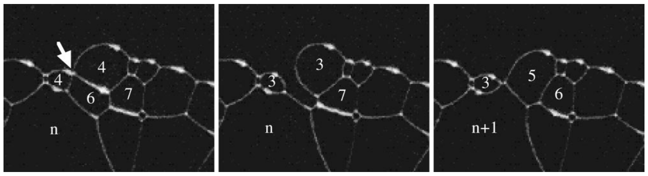

FIG. 3. Three successive pictures of the air/foam interface in a Hele-Shaw cell. The arrow indicates the wall that will break in the next picture. Topological indices of neighboring bubbles are given.

Figure 3 presents a series of three successive images of the interface in the HS cell. The arrow indicates the bubble that will break in the next step. Topological indices for neighboring bubbles are also given. One observes that every pop affects the topological indices of two neighboring bubbles, each losing one edge ($n\rightarrow n-1$). This is illustrated in Fig. 4. More importantly, a pop may induce additional topological rearrangements like vertex displacements that can also change the topological indices n of neighboring

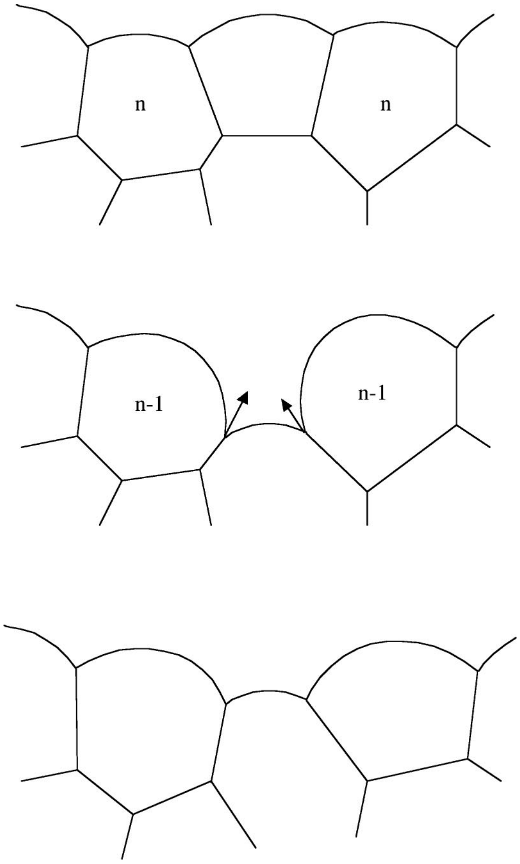

FIG. 4. Sketch of a pop that induces topological rearrangements. Two neighboring bubbles lose an edge. Due to vertex displacements, the bubble situated below starts to rise towards the top of the foam.

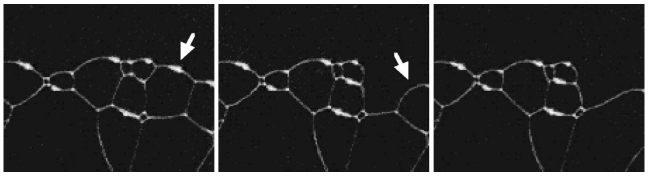

FIG. 5. Three successive pictures of the air/foam interface in a Hele-Shaw cell. This series follows the series of Fig. 3. The arrow indicates the wall that will break in the next picture.

bubbles. This is clearly seen on the images 2 and 3 of Fig. 3. Those rearrangements can be observed deep inside the foam. Indeed, when a bubble breaks at the interface, other bubbles start to rise towards the top of the foam. This is mainly due to vertex displacements towards the interface as illustrated by the sketch of Fig. 4. In fact, the hole left by the pop tends to be occupied by a rising bubble.

Figure 5 presents three successive pictures of the air/foam interface following the series of Fig. 3. On this series, one can observe that the popping of one bubble induces also the breaking of a neighboring bubble. Figure 4 illustrates well the spatial correlations for successive pops, correlations already emphasized in the previous section.

Figure 6 presents the topological distribution $f(n)$ of bubbles located at the air/foam interface. The data points are statistical averages for measurements made over 80 different images. The distribution $f(n)$ is fitted by a log-normal distribution. The mean topological number $\langle n \rangle$ is close to 6 as expected by the Euler formula [1]. Moreover, Fig. 6 exhibits the topological distribution of bubbles that are popping on the surface (circles). This distribution should be compared with the distribution of bubbles at the interface (dots). No major difference can be observed between both distributions. This indicates that no particular "topological selection" exists in the bubble breaking phenomenon. Slight differences are however observed for large n values but they are hindered by large uncertainties.

Another major observation is the following, the film which breaks in Fig. 3 is the smallest one. Intuitively, one would expect that long films are the more fragiles. We did not find any significative correlation for the length L of a film and its ability to break (frailty). Also, we did not find any significative correlation for the local curvature R of a film and its ability to break. In order to obtain quantitative results, we should measure the curvature and the length of breaking films on pictures. However, this kind of measurement is hindered by large uncertainties. There is an argument that supports the idea that the bubble breaking is independent of the local curvature and the bubble length. Indeed, the Lewis law [1] stipulates that the area A_n of n bubble is given by

$$A_n = \alpha n + \beta. \tag{2}$$

Since the bubble pops are indepedent of n, they should be independent of A_n and subsequently the bubble length L_n and the local curvature R_n.

Summarizing the results of the 2D observations: frailty of top bubbles is independent of the topological indices n of the bubbles. Observations suggest also that popping events are independent of the length of the film, and the curvature of the film. Popping bubbles lead to topological rearrangements spreading along the surface and inside the foam. The rising of some bubbles has been observed.

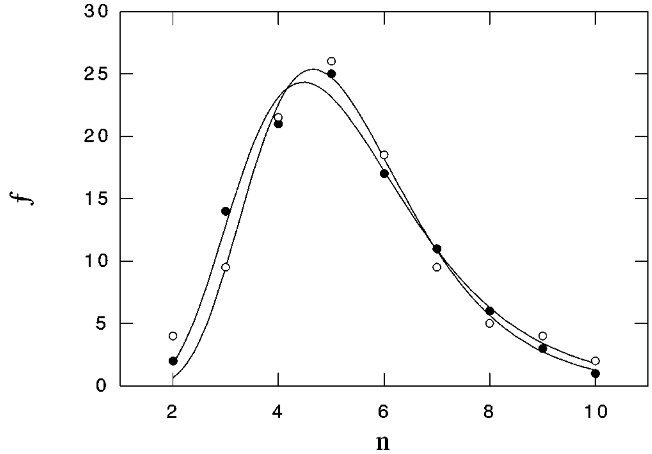

FIG. 6. (dots) Distribution of topological indices $f(n)$ for bubbles located at the air/foam interface. (circles) Distribution of the topological indices for popping bubbles.

III. DISCUSSION

We have emphasized temporal and spatial correlations for pop events/locations along the air/foam interface. In other words, pops do not occur at random within a cascade. One understands that each pop implies a topological change for neighboring bubbles that may propagate in the bulk of the foam as well as along the air/foam interface. Actually, it is unclear how topological rearrangements are connected to the cascade of popping events. Moreover, a careful image analysis suggests that there is no apparent selection for topological indices, no critical size, and no critical curvature for popping bubbles. One should note that simulations [5] assuming a breaking ability proportionnal to the length of the film lead to unrealistic foam coarsening. The origin of the spatiotemporal correlations should be attributed to a physical mechanism independent of the bubble type and thus independent of topological correlations like the Aboav-Weaire correlations.

Considering that a broad distribution of bubble types are fragile at the top of the foam, two different physical mechanisms responsible for temporal and spatial correlations can be proposed: (i) cascades due to the elasticity of the bubble walls, and (ii) cascades due to air displacement. In the former scenario, a pop may create an elastic shockwave, which propagates along the air/foam interface and which is mediated by the bubble walls. The subsequent oscillations of some bubbles may provoke their breaking. In the second scenario, the pop produces locally some air displacement that may be turbulent. Turbulence may affect neighboring bubbles and also provoke their breaking.

In the future, both proposed mechanisms will be further confronted to observations that will be performed with the help of high speed video equipment.

IV. CONCLUSION

In summary, our previous acoustic experiments [4] and the present study have put into evidence the intermittent and correlated character of exploding bubbles in collapsing dry foams. The dynamics of collapsing foams is discontinuous and evolves by sudden avalanches.

Moreover, we have discovered that a wide variety of bubble sizes participate in the phenomenon. Physical mechanisms for cascades should be found in the elastic properties of bubble walls or in the air displacement.

Future experiments concern the analysis of topological rearrangements near the air/foam interface at high sampling rates.

ACKNOWLEDGMENT

N.V. thanks N. Rivier for his comments and encouragements at the Eurofoam 2000 Conference.

---

[1] D. Weaire and S. Hutzler, *The Physics of Foams* (Clarendon Press, Oxford, 1999).
[2] S.A. Koehler, H.A. Stone, M.P. Brenner, and J. Eggers, Phys. Rev. E **58**, 2097 (1998).
[3] G.D. Burnett, J.J. Chae, W.Y. Tam, R.M.C. de Almeida, and M. Tabor, Phys. Rev. E **51**, 5788 (1995).
[4] N. Vandewalle, J.F. Lentz, S. Dorbolo, and F. Brisbois, Phys. Rev. Lett. **86**, 179 (2001).
[5] J.J. Chae and M. Tabor, Phys. Rev. E **55**, 598 (1997).
[6] S. Hutzler, D. Weaire, and S. Shah, Philos. Mag. Lett. **80**, 41 (2000).
[7] H.M. Ohlenbusch, T. Aste, B. Dubertret, and N. Rivier, Eur. Phys. J. B **2**, 211 (1998).