# Fingering Instabilities, Collapse, Avalanches and Self-Organized Criticality in Liquid Foams

Final Report

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## DISCLAIMER

# 1 Introduction

Foam is solid-like under low stress and fluid-like under high stress. It can sustain a small load elastically but a large one causes it to flow indefinitely. The shear elastic constant and the yield stress are two primary determinants of foam rheology. The plastic behavior which leads to yielding at a critical stress results from irreversible topological rearrangements provoked by increasing strain. When shear stress is present, a pair of adjacent bubbles can be squeezed apart by another pair, leading to a **T1** switching event. This local but abrupt topological change results in bubble-complexes rearranging from one metastable configuration to another. The resulting macroscopic dynamics is highly nonlinear and complex, involving large local motion that depends on correlations between nearby bubbles. The main goal of this study was to find the connection between the behavior of individual membranes and the whole network and to relate local rearrangements to global rheological properties of flowing foams.

Initially, we proposed three main directions of research: the effect of avalanches of structural rearrangements on rheological properties of two-dimensional foams, foam fingering and surfactant transport in three-dimensional foams. In the next section, we will briefly discuss our findings. More details can be found in the appended manuscripts (the first two[4, 5] are already submitted for publications, and the third one[6] is in final preparation).

# 2 Results

Our main findings relate to the structure/rheology relations for two-dimensional flowing foams. With our new digital DALSA CA-D4 camera with $1024 \times 1024$ resolution, which we acquired for this grant, and with the RAID system we constructed and the software we developed, we were able to improve significantly the quality of our images without sacrificing acquisition speed. The maximum frame rate we have achieved is about 30 frames per second, which is the same as for analog cameras. (For example, one can easily see the difference in images quality in Figure 2 of Ref. [6].)

We have examined the motion of large bubbles through ordered and disordered foams. In ordered foam, a large bubble (with smallest dimension of several average bubble diameters) moves with the same speed as all surrounding bubbles. While in disordered foams, the behavior of large bubbles (of the same size as in the experiments on ordered foams) is qualitatively different. First of all, it tries to rotate so that the longest dimension is perpendicular to the direction of the flow. When rotation is almost complete, the bubble cannot sustain a convex shape anymore, and begins to bend. After assuming a bow shape, the bubble begins to accelerate and moves forward with respect to the mean flow, meandering around the center of the channel. Sometimes it breaks into parts. There is low limit for the bubble size (to be more precise, for the ratio of volumes of large and average bubbles) of bubbles which show such "snake" motion. This minimal volume decreases with increasing average foam flow rate and with the width of the bubble size distribution for the "base" foam.

We have also conducted extensive experiments on foam flows through various constrictions and around circular obstacles. Because foam is quite different from common fluids because of its discrete structure, and exhibits both elastic and fluid (or plastic) responses under mechanical deformation, we needed to develop a consistent method for extracting the rheological properties of sheared foam (*i.e.* the stress-strain relationship) from experimental data. The problem is that no existing formalism derived from microscopic principles encompasses both foam's fluid-like and solid-like aspects. Hence, we [4] define the *statistical strain tensor* to quantify the intuitive notion of stored deformation. This tensor links microscopic and mesoscopic descriptions of the material, and generalizes the usual elastic definition of strain, allowing a unified theory of elasticity and plasticity. We have successfully applied this method to analyze our data on two-dimensional foam steadily flowing through a constriction [5] and around an obstacle. We have found that within the main portion of the flow domain, (except some regions near the walls) the foam has the elastic properties of a (linear and isotropic) continuous medium, such that its flow can be described by a simple effective viscosity whose form we have determined. The continuum description, however, fails to capture all features of flowing foams. For example, as a two-dimensional foam flows around an obstacle, we find a sharp maximum of the average foam velocity just behind the obstacle. In contrast, for a usual Newtonian fluid, we expect the smallest liquid velocity in this region which is the trailing stagnation point. For the same foam flowing through a constriction, we find regions within the flow domain, where

the time-averaged streamlines can split, merge or detach from the wall, which is impossible for ordinary fluids. Again, we find local maxima of the average foam velocity near the corners, where we classically expect a stagnation region with the slowest flow, or, for some non-newtonian fluids, weak recirculation. We [6] explain these phenomena qualitatively and discuss possible mathematical descriptions of such foam flows. The main reason for such strange foam behavior is the presence of high-stress regions in the flow causing structural changes (in particular, topological rearrangements (T1 processes)) to occur at preferred locations. T1s may happen, for example, behind the obstacle, at some "favorite" points near the corner walls or "along the streamlines"(see Figures 2 and 5 of Ref.[6]). Hence, the complete description requires some type of matched asymptotic analysis — including careful consideration of foam dynamics in relatively small "high-stress" regions, obtaining the velocity "jump" from discrete analysis and subsequent matching to the large-scale flow described by ordinary fluid mechanics. We may determine the limiting normal and/or shear stress (which, in fact, determines the spatial extent of the inner (microscopic) region) by considering the dynamics of a single T1 process on the scale of few directly involved soap films. To match with the outer (macroscopic) region, we can develop an "activation energy" model to determine when the large-scale outer flow provides sufficient pressure and/or shear to induce cascades of T1s at certain locations. Together with the already determined effect of a single T1 on foam velocity, this analysis will provide the frequency of such events in "dangerous" regions of the flow and hence the amplitude and spatial extent of disturbances in the macroscopic velocity. While this theoretical analysis was outside of the scope of this grant, the work covered here has provided the data for this analysis and we are working towards such a complete model.

We attempted to investigate surfactant transport in foams by supplying fluid without surfactant to the top of the foam column. While we expected the rate of surfactant transport from the lamellae to depend on foam wetness and structure, we did not detect appreciable difference in foam life-time. All foams collapsed almost immediately because we were unable to match the surface tensions of basic and added fluids (using only literature data but without equipment to measure the surface tension of actual solutions). As a result, the jump in surface tension induced fast flow of liquid out of the lamellae which promoted film rupture, regardless of other conditions. We are currently purchasing instruments to measure dynamic surface tension and will repeat these experiments.

We also tried to initiate viscous fingering in three-dimensional foams by supplying liquid on the top of the foam head and using MRI to capture the internal structure of the developed fingers. Our hope was to determine the mechanism of finger formation and wavelength selection and to find the relationship between foam structure and the critical liquid flow rate. Unfortunately, we found that our large MRI cell (a cylinder with internal diameter of 45 mm) is too narrow to obtain multiple fingers. When the liquid flow rate exceeds some critical value, the flow instability always forms one convective roll of bubbles, regardless of bubble size, width of bubble size distribution and composition of base fluid. Under such conditions, MRI cannot provide much interesting structural information. Hence, we investigated such convection optically, using a rectangular cell with about twice the cross-sectional area of the MRI cell. Surprisingly, though this cell also has a rather small aspect ratio, we obtained multiple fingers – in a few experiments we obtained two unequal rolls instead of one, we are currently working to make these experiments more reproducible. One difficulty in the larger cell, we to achieve uniform liquid supply to the top of the foam head. While we have obtained some interesting results on the dependence of critical flow rate on base fluid viscosity, bubble size (increase in viscosity and decrease in bubble size reduce foam stability) and the width of the bubble size distribution (polydisperse foam is more stable), this work is not yet published. Currently, it continues with support from other grants.

Dr. Glazier has presented research supported by this grant at the:

1. New York University, Department of Physics, Colloquium, New York, NY, February 10th, 2000.
2. Eurofoam 2000, Technical University, Delft, Delft, the Netherlands, June 7, 2000
3. Leiden University, Department of Physical and Macromolecular Chemistry, Leiden, the Netherlands, June 13, 2000.
4. National Polytechnic Institute of Grenoble, Department of Physical Engineering and Mechanics of Materials, Grenoble, France, October 12, 2000.
5. University of Lyon, Claude Bernard, Department of Materials Physics, Lyon, France, 10/13/00.

6. University of Paris VI/VII, Jussieu, Joint Condensed Matter, Biophysics Seminar, Paris, France, November 11, 2000.
7. Laboratoire de Physique, Ecole Normale Superieure de Lyon, Lyon, France, December 14, 2000.
8. Department of Physics, University of South Florida, March 23, 2001.
9. Interdisciplinary Center in Nonlinear Science, Northwestern University, Evanston, IL, December 7, 2001.
10. Plasticity 2002, Aruba, January 7, 2002.
11. Eurofoam 2002, Manchester, England, July 9, 2002.
12. Foams and Minimal Surfaces, Isaac Newton Institute, Cambridge, England, August 6, 2002.
13. GEOMES Conference, Max Planck Institute, Dresden, Germany, October 22, 2002.

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  3. SengKai Wong
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[5] M. Asipauskas, M. Aubouy, J. A. Glazier, F. Graner and Y. Jiang, "Continuum Mechanics of Plastic Deformations: the Example of Two-Dimensional Flowing Foams", *to appear Granular Materials*, 2003.

[6] M. Asipauskas, I. Veretennikov, A. Indeikina and J. Glazier, "Large-scale foam flows: discrete effects and limits of continuum approach", *in preparation.*

[7] I. Veretennikov, and *et al.*, "Mechanism for Helical Gel Formation from Evaporation of Colloidal Solutions", *Langmuir* **18** (23), 8792 – 8798, 2002.