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DISSIPATION IN 2D FOAM FLOW

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Summary We study the dynamical behavior of large bubbles embedded in the plug flow of a 2D foam made of smallest bubbles. At a critical velocity the foam structure becomes instable and the largest bubbles migrate through the foam faster than the mean flow. This size segregation is due to viscous effects and happens only for flow velocities larger than a given threshold. We compare our theoretical predictions (*Cantat, Delannay, Phys. Rev. E. 2003*) to experimental and numerical recent results and thus we give a extended description of this original instability involving the full visco-elastic properties of the foam. We show that the phenomenon can induce flow destabilization with dramatic effects on foam transport, like avalanches of film ruptures and flow intermittency.

INTRODUCTION

A monodisperse foam subject to a pressure gradient in a Hele Shaw cell with smooth lateral boundaries gives rise to a simple plug flow. In contrast, in case of a polydisperse foam, the plug flow undergoes a sharp dynamical transition at a critical velocity threshold v_t, depending on the aspect ratio. Larger bubbles insinuate themselves trough the foam faster than the mean flow. This phenomenon cannot be explained with a quasi-static point of view. In fact, unlike shear flows, no external constraint enforces bubble reorganization, and changes in the foam structure are intrinsically related to dissipative processes. A large bubble gives rise to a smaller local film density and, consequently, to a low effective viscosity averaged on a mesoscopic scale. Like for the Saffman Taylor instability, the large bubbles migration is driven by viscosity contrast. However, the coupling with the elasto-plastic response of the film network leads to subtle specific behaviors.

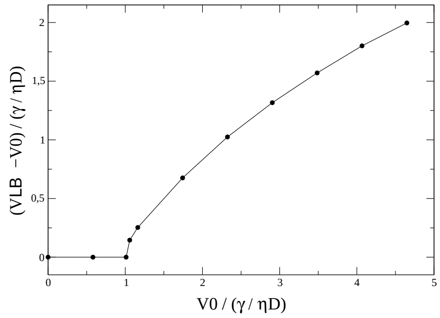
Viscous dissipation

A crucial parameter in this problem is the viscous force exerted by the wall. Even at relatively small velocity, this force is important in foam rheology in a quasi two-dimensional geometry (see e.g. [1]), or in a classical rheometer for which sliding effects on the plates may be crucial. In the "2D" experiments a foam is confined between two parallel glass plates, which are separated by a distance smaller than the bubble radius (typically by a few millimeters). When the whole foam is pushed ahead between the plates, complex flows take place in the network of the Plateau borders as they slide on the plates. Most of the injected energy is dissipated in this process, which involves nonlinearities arising from the deformability of the films delimiting the Plateau borders. A scaling relation for the pressure drop in relation to the flow velocity V of the bubbles $P \sim V^{2/3}$ has been found in the regime of small capillary numbers ($Ca = \eta V/\gamma \ll 1$, where η is the viscosity of the liquid phase and γ the surface tension at the interface) [2]. Our experimental results are in good agreement with the previous law. The dissipation seems to be dominated by the normal motion of the films leading thus to the following force expression [3]

$$F = \lambda \, L_{proj} \, \gamma \, Ca^{2/3} \, , \tag{1}$$

with L_{proj} the length of contact between foam and glass, projected in the direction of motion and λ a numerical prefactor. This result is used in the numerical simulation detailed below.

Analytical and numerical predictions



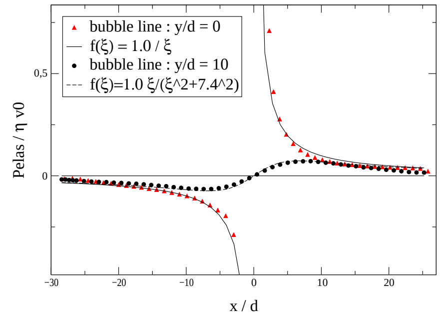


Figure 1. *(a) Relative velocity of one large bubble embedded in a monodisperse foam flowing at velocity v_0. (b) Pressure for two representative bubbles columns oriented along the flow, once P_{eq} and the average pressure gradient have been subtracted. Symbols are numerical predictions at the positions shown and lines are mathematical functions indicated on the legend. The theory predicts a function of similar shape $f(\xi) = 1.9\xi/(\xi^2 + (y/d)^2)$.*

The presence of a large bubble locally decreases the dissipation and thus the driving force needed to produce the flow. The elastic network distortion adjusts to compensate for this force discrepancy at low velocity, and the plug flow is maintained. Past a critical threshold, the plastic limit is reached and the compensation is driven instead by viscous forces, thus making the films around the large bubble move faster than the mean flow. The analytical predictions are based on a mesoscopic description of the foam involving a pure elastic response at low stress and a plastic threshold γ/d, with d the typical bubble size. We get a velocity threshold $v_t \sim \gamma/(\eta D)$ (with D the large bubble diameter) and the pressure fields given in picture 2(b) [4]. The numerical simulation is based on the vertex model [5] and is performed in a periodic array. The initial condition is an ordered monodisperse foam of bubbles with uniform size and a single large bubble LB. At each time step, a bubble line far from LB is pushed at constant velocity $v_0\mathbf{u}_x$, and other vertices are displaced with velocities ensuring the balance between viscous forces, tension and pressure. A neighbor swapping event (T_1 process) is performed when two vertices become closer than a given value ϵ. After a transient depending on the initial large bubble shape, a stationary regime is reached in which the large bubble exhibits a regular almond shape oriented along the flow. Plug flows are observed at low velocity. However, as Fig.1(a) illustrates, the large bubble reaches a velocity $v_{LB} > v_0$ for velocities faster than v_t.

Experimental results

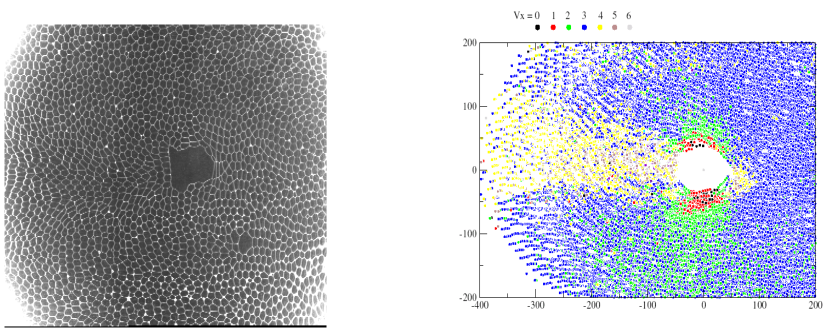


Figure 2. *(a) 2D foam image, flowing to the right. (b) Velocity field around the large bubble, the color indicates the velocity component in the mean flow direction.*

Our channel is made with two horizontal glass plates ($1.5m \times 0.6m$) connected to a vertical cell where the foam is produced and drained. Foaming solution is SDS 3g/l, dodecanol 0.01 g/l, glycerol 10% and water. The foam is continuously produced by nitrogen blowing at a controlled rate and the large bubble is obtained with pulsed infra red YAG laser. Images are recorded and analyzed with the software Visilog (see a raw image Fig. 2(a)). We get the full velocity field as shown picture 2(b). We determine the threshold instability and the dynamical behavior after this threshold.

Conclusion

This study naturally leads to new questions on the dynamic interactions between several large bubbles in a bidisperse or polydisperse foam. In particular, we have experimentally observed the formation of long streamwise chains of large bubbles percolating through the Hele Shaw cell. This phenomenon has profound effects on the flow. These chains transport the major part of the volume flux, at high speed. The soap films involved are submitted to high stresses and avalanches of film breakage occur frequently, thus destroying suddenly the whole column and short circuiting the overall pressure drop until new foam fulfill again the free passage. This process related to the large bubbles interactions and organization is highly undesirable in industrial flow and further studies of this phenomenon are thus of practical interest.

References

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