Flow of Foams

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Summary

Foams are aggregates of air bubbles that are surrounded by a thin layer of liquid. They are intrinsically unstable, but adding a surfactant like dishwashing fluid or soap to the fluid can prolong the lifetime of bubbles up to hours. Individual foam bubbles obey rather simple interaction laws: foam bubbles are elastic, that is, if they are deformed they will bounce back and if a foam bubble is sliding past another object it will feel a drag force. Furthermore, foam bubbles are often macroscopic (between 0.1 mm and 1 cm) meaning that they will not jiggle around at room temperature.

Despite the simplicity of its constituents a foam behaves in a complicated manner. Consider the collection of bubbles which constitute a column of shaving cream, for example. This conglomerate can carry its own weight like a solid and will bounce back when gently poked, while it will flow like a liquid once sufficiently strong forcing is applied. The threshold stress that leads to flow is often referred to as the *yield stress*. Furthermore, the faster one drives the foam, the less the foam will resist the flow, which is called *shear-thinning*. This behaviour is common to a larger class of materials such as sandpiles, emulsions (mayonnaise), pastes (peanut butter) and colloidal systems (toothpaste) which are all disordered packings of many particles.

The big challenge in the field of disordered materials is to relate the properties of the individual particles to the behavior of the material as a whole. In order to do this one needs to simultaneously measure the global behaviour and the motion and state of all the individual particles. However, the white colour of most of the materials mentioned above signals the

fact that these media strongly scatter light, and thus one cannot directly look inside.

In this thesis, we have gained insight in the connection between the local and global behaviour in foams by retreating to two dimensions. In chapter 2, we describe an experiment in which we induce flow in a single disordered layer of foam bubbles bound between the surface of a soapy solution and a glass plate. We obtain the averaged velocity profiles as a function of the applied shear rate and in addition we obtain information on the local flow behaviour by very careful measurements of the relation between forces and deformations in foam with a rheometer. We find that by only considering that the viscous drag forces on the bubbles need to balance — the drag forces result from the bubble sliding past another bubble or sliding past the confining glass plate — we can explain the observed shape of the velocity profiles. From the force balance we can deduce an expression for the average drag force between bubbles which we can compare to direct measurements with the rheometer. Surprisingly, we find that the average local drag force between neighbouring bubbles in a disordered, flowing foam is different from the actual local drag force between two bubbles that move past each other in an orderly fashion, as in the rheometer. We attribute the difference to the erratic flow that occurs in the disordered foam, which on average enhances the amount of drag a bubble experiences during flow. We substantiate this picture further by shearing an ordered, crystalline foam. In that case we see that our drag force balance model fits the date provided the local drag force between bubbles is indeed the same as the one we measured using rheomtry.

In chapter 3 we continue in the same vein, but this time we shear two-dimensional disordered foam layers in a circular geometry called a Couette cell. In this geometry, the foams are contained inside two concentric circles and the inner disc is rotating. In the linear geometry used in chapter 2 the effect of a yield stress in the foam cannot be observed. However, in a Couette geometry its signature should in principle be visible, due to the curvature in this system. Moreover, the Couette geometry allows for runs both with and without the glass top plate, and we have investigated the effect of the glass plate in further detail.

We again record average velocity profiles and by adapting our drag force balance model to the curved coordinates we extract the behaviour of the bubble-bubble drag force by fitting the model to the data. When the foam is not confined by the glass plate, it appears to be a lot more shear thinning than when it is confined. We speculate that the presence of the glass plate alters the fluctuations in a disordered foam, much as the disorder itself did in chapter 2, and we suggest to measure the influence of the glass plate on the fluctuations by particle tracking. In both cases we observe no signature of a yield stress, in fact, if we image the velocity profiles while simultaneously measuring the global force-deformation rate with a rheometer, we find that locally, the foam does not cease to flow while globally the foam appears to be below the yield stress.

In chapter 4 we change gears and explore the applicability of foams to experimentally probe the nature of the jamming transition. The jamming framework was introduced to unify different classes of disordered materials that exhibit a transition between fluid-like and solid-like behaviour which is termed the jamming transition. Foams can be made to lose their solid-like behaviour by applying a stress larger than the yield stress or by lowering the packing density of foam bubbles. In order to vary this packing fraction, we vary the gap between glass plate and liquid surface (this gap was constant in chapters 2 and 3). In chapter 4 we thus explore the jamming transition as a function of density.

We first describe techniques we have developed to characterise the bubble density in our experimental geometry and then investigate the foam viscosity as a function of the distance to the transition. Finally, we explore mechanical and statistical measures that probe the physical nature of the jamming transition and we find promising indications that foams are indeed eminently suited to probe the jamming framework.