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Bubble ribbons under imposed flow

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ABSTRACT

Bubble rafts consisting of a single layer of bubbles floating on the surface of water have proven to be an important model system for studying materials ranging from crystalline systems to amorphous solids to complex fluids. An interesting question in foams and complex fluids is how the detailed nature of the bubble–bubble interactions determines the resulting stable states of the system, especially in the context of different approaches to generating the foam or complex fluid. In this paper, we report on the generation of bubble rafts using an imposed flow. The flow breaks the symmetry of the system and allows for the generation of stable bubble ribbons of many different widths. We report on the transition between ribbons of different widths and the ultimate separation of the system into multiple small ribbons. An interesting feature of the system is the stability of very narrow ribbons against self-folding. In principle, folding of the ribbons would produce states with lower global energy. Therefore, understanding the energy barriers and dynamics involved in the prevention of this transition will play a role in deepening our understanding of these systems.

1. Introduction

One of the interesting, and challenging, elements of complex fluids is the wide range of interactions between the particles due to the rich variety of constituent particles. For example, dry granular materials generally are purely repulsive systems with frictional forces between the grains [1–4]. Colloidal systems can be designed to be purely repulsive, or have attractive forces [5,6]. Depending on the details, one can adjust the range of the attractive forces as well. Dry foams, gas bubbles with extremely thin liquid walls, tend to be dominated by the interfacial tension of the walls, but there can be effective interactions that are mediated by the shape changes of the bubbles under compression and extension [7–9]. Despite these significant differences at the level of microscopic details, there are surprising similarities between the macroscopic response of these systems to mechanical deformations [10–18]. Therefore, it remains an interesting question as to how the details of the interactions contribute to and influence the response.

In addition to the general question of mechanical response, particle interactions can have a significant impact on the stability of underlying structures that can be formed in these systems. Especially when one considers different processes for the formation of the states. For example, diffusion limited aggregation is one method of building up layers of material [19–21]. In this process, particles are allowed to diffuse from a source to the location where the material is being formed. Depending on the nature of the particle interactions, and other external conditions, one observes very different final morphologies using the same basic process. Another approach to forming a material structure is to deposit the material in the presence of a flow field. It is this process that we focus on here using bubble rafts.

There is a long history of using bubble, or Bragg, rafts, i.e. a single layer of bubbles on the air-water interface, to understand fundamental physics aspects of atomic materials [22,23]. Bragg first utilized these systems for the study of crystalline materials, and later their application was extended to amorphous systems. This work included detailed calculations to map the bubble-bubble interactions to standard inter-atomic potentials. The general approach is to create a uniform sheet of bubbles of either a single size or a distribution of sizes. The bubbles are the analogues of the atoms in the molecular system. Once formed, one can easily study defect formation, defect dynamics, and mechanical properties.

In addition to being a model for atomic systems, bubble rafts are an interesting system in their own right. Their properties put them at the intersection between wet foams and bubble systems. On the one hand, they are a collection of gas bubbles with liquid walls, where the bubbles remain spherical. This is essentially the definition of a wet foam. However, because of their location at the surface of water, one can

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achieve arrangements of bubbles where there are gaps, with no fluid. This is analogous to a particle system with the bubbles acting as individual particles, not as a collection of bubbles with liquid walls. Finally, the bubbles experience a long range capillary force arising from the deformation of the fluid surface [24]. This combination of properties have lead to bubble rafts being used to study a wide-range of phenomena, ranging from defect dynamics [25–27], to rheology [28–31], to failure mechanics [32,33], and in this study, to material deposition under flow.

Briefly, to generate bubble raft formation in a flow field, we build on the basic method of forming bubble rafts that uses flowing air gas through a single needle immersed in a soap solution. This method produces a single bubble at a time that floats to the surface and due to the attractive forces between the bubbles, ultimately forms the bubble raft. Without an applied flow, this process is analogous to the formation of molecular sheets through a vapor deposition process. In the case of bubble rafts, if the needle is held in a fixed position, a multilayer sheet is formed. Therefore, if a single layer sheet is desired, the needle is general moved slowly around the sheet as it forms, so as to avoid multilayer formation. If the needle is moved in a fixed direction, one can generate a ribbon of bubbles instead of a single sheet. In this case, we find that the width of the ribbon of bubbles is a well-defined function of the speed at which the needle is moved. The rest of the paper is organized as follows. We first describe the apparatus and the details of the bubble raft formation. Second, we discuss the results of using different pulling speeds and bubble solutions. Finally, we discuss the implications of the results.

2. Experimental methods

As discussed above, bubble rafts are formed by flowing air gas through a bubble solution. For the work reported here, we use a standard bubble solution consisting of 80% DI water, 15% glycerin, and 5% commercially available bubble solution by volume. This generates bubble rafts that are stable for 1–2 hours. The typical experimental process are shorter than two minutes and we do not observe any coarsening during the process. For this work, we focus on monodisperse systems, producing bubbles with a diameter (d_{bubble}) of 1.2 mm.

A schematic of the apparatus is illustrated in Fig. 1. In order to generate a controlled flow for the bubble generation, we use a needle that is affixed to a rigid bar. The bar is mounted on two driving belts. The belts are driven at a constant speed using two, computer-controlled stepper motors. We studied the generation of bubble rafts using a pulling speed that ranged from 2 mm/s to 16 mm/s.

To generate the bubbles at a steady rate, and constant size, a computer controlled syringe pump was used. For all of the experiments reported on here, bubbles were generated at a rate (f_{bubble}) of 5 bubbles per second. This sets a natural time scale for the experiments. Combining this time scale with the bubble diameter provides a natural speed scale $v_{sc} = v_{\mathrm{Pulling}}/(f_{\mathrm{bubble}} * d_{\mathrm{bubble}}) = 1/6 * v_{\mathrm{Pulling}}$. When reporting the phase diagram for ribbon generation, we used this natural speed to scale the needle pulling speed.

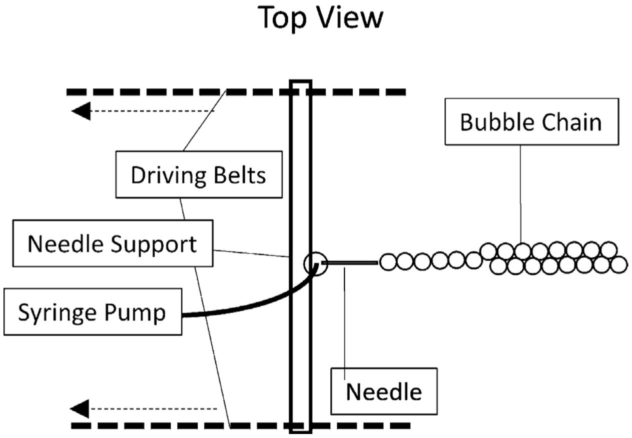

Fig. 1. An image of the apparatus used to generate bubble ribbons. The main components of the apparatus are indicated in the figure. The key elements are syringe pump that is used to generate bubbles at a constant rate and the drive chains used to move the needle at a constant speed.

An important aspect of the bubble raft is the attractive forces present in the system. Essentially, there are two main attractive forces: (1) a long range capillary force arising from the deformation of the fluid surface between two particles [24,34]; and (2) a short-range contact force due to the surface tension of shared film that is formed when two bubbles are in contact. Fig. 2 illustrates the energy of a long range capillary force schematically between two particles from Ref. [34]. In terms of the energy of the system, once the bubbles are in contact, the lowest energy states will generally be clusters that maximize the number of bubbles with six neighbors. Particularly relevant for our work, even for clusters as small as six bubbles, the lowest energy states are clusters and not a chain of bubbles [35]. Fig. 3 shows the two most frequently occurring bubble clusters and a bubble chain from ref. [35]. The frequency of occurrence of the clusters was 0.5 and 0.4, respectively. The chain occurred at a frequency significantly less than 0.1. It should be noted that there is only a 2% difference in the energy of the most frequently occurring state and the bubble chain. We will return to this point in our discussion of the bubble chains stability.

3. Results

As a function of the pulling speed of the needle, we observe the following four main regimes of behavior: (a) formation of a bubble sheet, generally multilayer; (b) formation of ribbons of decreasing width as a function of increasing speed as shown in Fig. 4(A)(B)(C); (c) formation of ribbons precisely two bubbles wide as shown in Fig. 4(D); and (d) formation of two bubble wide ribbons of various lengths as shown in Fig. 4(E) and (F).

It is worth noting a few key features of the bubble ribbons. First, each ribbon has a clearly dominant width given by a discrete number of bubbles. However, for all the cases of ribbons with a width of greater than two bubbles, we generally observe a significant number of defects in the form of additional bubbles on the outer edges of the ribbon, or even kinks and bends in the formation of the ribbon. Therefore, when we compute the average width of any given ribbon, it will not be an integer number of bubbles. In fact, the variation in the average width at a given pulling speed is an indirect measure of the number of defects and the probability of getting a defect.

A second feature is the nature of the transition to ribbons with a width of only two bubbles. Ultimately, we reach a state where ribbons consisting of exactly two bubbles are formed with a high degree of reliability. This transition as a function of pulling speed is illustrated in Fig. 5. A box and whisker plot format is used so that both the decrease in the average width and the decrease in the variation in the average width can be shown. In both Figs. 5 and 6 , the mean width is shown as a point on the graph. The line in the box represents the median value, and the edges of the box are the 25% and 75% points. The “whiskers”, bars extending from the box, are the 5% and 95% values. The relative collapse of the box at $v_{sc} = 0.8$ indicates the transition to mostly error-free ribbons of width 2, with the apparent complete reliability of producing ribbons of width two occurring at $v_{sc} = 0.9$. At this speed, the ribbons are sufficiently error free that the box is smaller than the point size.

An interesting feature of the two-bubble wide ribbons is their stability. The states illustrated in Fig. 4 provides examples of the different two-bubble states that are observed. First, for ribbons formed around $v_{sc} = 0.9$, we are able to form stable ribbons up a length of 12 cm or greater (limited by the size of the trough) An example of a full length, two-bubble ribbon is given in Fig. 7. One feature that is observable in