Foams in microfluidics

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Abstract:

We present an experimental investigation of the agglomeration of microbubbles into a 2D microfoam and its flow in a rectangular microchannel. Using a flow-focusing method, we produce the foam in situ on a microfluidic chip. It is possible to vary the liquid fraction over a large range. Observation by microscope allows visualizing the transition from separated bubbles to a microfoam in which bubbles are closely packed and separated by thin films. The foam flow rate depends non-linearly on the applied gas pressure displaying a threshold due to capillarity. Strong discontinuities in the flow rate appear when the number of bubbles in the channel width changes, reflecting the discrete nature of the foam topology.

Résumé:

Nous présentons une étude expérimentale de l’obtention d’une micromousse 2D à partir de l’agglomération de microbulles, et son écoulement dans un microcanal rectangulaire. Nous utilisons la méthode dite de "flow-focusing" pour produire une mousse directement à l’intérieur de la puce microfluidique. Il est possible de faire varier la fraction liquide sur une large gamme. L’observation au microscope permet de visualiser la transition d’un ensemble de bulles disjointes à une micromousse, dans laquelle les bulles sont étroitement agglomérées et séparées par des films minces. Le débit de la micromousse dépend non-linéairement de la pression du gaz appliquée, et présente une pression seuil due à la capillarité. De fortes discontinuités apparaissent quand le nombre de bulles dans la largeur du canal change, ce qui reflète la nature discrète de la topologie des mousse.

Key-words:

Foams ; Microfluidics ;

1 Introduction

Two phase microflows like the one of microemulsions, microbubbles, microdrops and recently ordered microbubble lattices attract considerable attention [Anna et al. (2003), Cubaud et al. (2004), Garstecki et al. (2004), Garstecki et al. (2005), Drenckhan et al. (2005)]. To these we would like to add a precise study of dry and controlled microfoams. Their application in a lab-on-a-chip context provides the possibility for the efficient handling of series of gas pockets, and allows to create microchemical reactors that are both very rapid and highly parallelized.

Specifically, the gas-liquid interface of microfoams provides a transport location for amphiphilic molecules, with a hydrophilic head and a hydrophobic tail. A decrease in size increases the surface to volume ratio; hence, microfoams could be used as an efficient carrier for proteins or lipids at high concentration.

Microfoams offer advantages compared to foams at larger scales for the study of foam properties as microfoams are very stable and well controlled. First, the absence of vertical drainage on the small length scales of a microfluidic system creates liquid profiles in the foam films that are constant over time and do not show an asymmetry due to gravity. Another advantage is that because of the low Reynolds numbers involved, the amount of gas produced during bubbling
is very stable with a nearly monodisperse bubble volume distribution. The amount of liquid (liquid fraction) can be reproducibly controlled as it is governed by the input parameters.

A set of basic operations using specific channel geometries necessary for manipulating series of bubbles, termed “discrete microfluidics”, has been demonstrated at the millimeter scale [Drenckhan et al. (2005)] in a “dry” foam, where the liquid content is low compared to the gas content. To down-scale these operations and adapt them for microfluidics requires producing a microfoam and information about its flow characteristics.

We investigate the continuous production of a two phase gas-liquid flow in a flow-focusing device, and the transitions between different regimes of bubble formation, so as to reach microfoams, thereby extending the studies of [Garstecki et al. (2004)] to low liquid fractions. In a microfluidic flow-focusing device, a flowing gas thread is forced, by the co-flowing surrounding liquid, into a small orifice, where the gas thread breaks up at regular time intervals [Garstecki et al. (2004), Garstecki et al. (2005)]. At low liquid to total flow rate ratio this will create a microfoam.

Figure 1: For increasing gas pressure the bubble volume grows. Bubbles start touching and a foam is formed. From top to bottom: bubbly flow, 4 rows (F4), 3 rows (F3), 2 rows (F2) and 1 row of bubbles (F1). Liquid flow rate $Q_l = 4 \mu l/min$. Gas pressure $P_g$ increases from 1 to 5 kPa between the upper and lower image.

2 Materials and methods

We use a conventional flow-focusing geometry [Anna et al. (2003), Garstecki et al. (2004), Garstecki et al. (2004)): an inlet channel for the liquid, another one for the gas, both ending in a small orifice followed by a straight channel section (orifice width $w_{or} = 100 \mu m$, channel height varying between channels from $h = 8$ to $200 \mu m$ and channel aspect ratios (height to width ratio) varying from 0.3 to 0.02. The walls of the system are made in PDMS glued to a glass cover slide. A syringe pump (11 PicoPlus, Harvard Apparatus) is used to push the liquid (deionized
water with 10% commercial dishwashing detergent Dreft, Proctor & Gamble). For the dispersed gas phase we use nitrogen supplied from a pressurized tank via a pressure reduction valve. The exit is at atmospheric pressure. Therefore we have access to the imposed pressure drop over the total system (orifice and outlet channel). We use a CMOS camera (F131B, Allied Vision Technologies) connected to a macro lens to capture still images and to record movies of the two-phase flow. Via image analysis, we extract the bubble volume \( V_b \), bubble formation frequency \( f \), from which we deduce the gas flow rate \( Q_g = V_b f \).

3 Microfoam flow

To study bubble formation and the accompanying bubble topology in the channel we vary the gas pressure while keeping the liquid flow rate constant. In this way we scan the complete pressure range for which bubbles are formed at that liquid flow rate. See 1.

We observe a minimum pressure \( P_c \) for which bubbles form. For lower pressures the gas-liquid interface does not enter the orifice. This effect is probably due to the capillary pressure [Raven et al. (2006)]. Above the initial pressure \( P_c \), a gas thread is forced into the orifice and fills a bubble after the orifice. This thread pinches off and releases the bubble. After break-up, the gas-liquid interface retracts to its initial position.

For increasing \( P_g \), bubble volume grows and the bubbles start touching. Five possible structures appear, according to the flow rate: bubbly flow, or a foam with four, three, two or one row (F4, F3, F2 and F1 respectively). For much higher \( P_g \) the gas thread stops breaking up and a stratified liquid-gas flow is observed.

We now turn to the flow of a foam in the microchannel after formation. When we measure the average gas flow rate \( Q_g \) as a function of the applied gas pressure drop \( P_g \), we observe a highly non-linear response (see 2). We find: a threshold, a non-linear slope and a discontinuity upon the transition from a F2 to a F1 foam.

2 shows a threshold in pressure drop for the establishment of bubbly flow. It is found to be \( 1.0 + / − 0.1 \; kPa \), if this parameter is left free in the fit for liquid flow rates varying between 4 to 40 µl/min (data not shown). It is compatible with the above explanation by a capillary effect at the orifice.

The flow rate is highly non-linear above the threshold, see 2. The gas flow rate increases faster than a linear function of pressure. A fit of the pressure drop \( P_{\text{channel}} \) by \( Q_g^{2/3} \) gives a correct agreement (data not shown) [Raven et al. (2006)].

The structure transition from a F2 to a F1 foam induces a discontinuous decrease of the gas flow rate (2). This is a signature of the discrete character of the foam. It can be explained by relating foam rheology to foam topology. Dissipation mainly occurs in the liquid films, close to the walls [Bretherton (1961), Cantat et al. (2004)]. Foam resistance to flow can be related to the total length of liquid films between bubbles sliding over the channel walls. The orientation of these films plays a role: a film oriented in the direction normal to flow dissipates more than a film oriented in the tangential direction. One can show that upon the transition from F2 to F1 the number of films increases together with an increased orientation in the direction normal to flow [Raven et al. (2006), Raven et al. (2006a)]. Therefore the resistance increases explaining the discontinuity.

4 Compressible foams: local pressure measurement

Local pressure measurements in microfluidic channels are hard to perform. For the moment it seems troublesome to downscale conventional measurement techniques. A possible method
Figure 2: Highly non-linear foam rheology. Gas flowrate $Q_g$ vs. gas pressure drop $P_g$ for liquid flowrate $Q_l = 20 \mu l/min$. 
suited for a microfoam would be to use the compressibility of the gas phase. By making the outlet channel very long, the total pressure drop becomes that big that a bubble volume change upon transiting from high-pressure to low-pressure will take place. Assuming isothermal decompression the volume of a bubble can be related to its pressure using a reference pressure $P_0$ and volume $V_0$: $PV = P_0V_0$. Care has to be taken though due to the solubility of the gas in the liquid. Gas solving into the liquid upstream (high pressure) and going back into the bubble downstream (low pressure) could lead to an overestimation of the actual pressure difference.

5 Conclusions

We describe the formation and flow of a foam in a confined microchannel. The transition from bubbly flow to foam depends on the liquid fraction which is governed by the interplay between control parameters $P_g$ and $Q_l$ and the channel geometry. Foam flow and bubbly flow in microchannels are highly non-linear. The flow-focusing orifice induces a threshold $P_c$ due to capillary effects in the flow rate to pressure characteristic. The data for both bubbly and foam flow give good agreement to $P_g-P_c = Q_g^{2/3}$. The prefactor in this relation depends on the dissipation in the channel related to the topology. We also show a possible way to measure pressure locally in a microfoam.

References


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Figure 3: a) Image of a compressible F1 foam. Bubble decompress with position in the outlet channel due to decreasing pressure. The outlet is at ambient pressure, the inlet at $P_g = 42kPa$. Liquid flow rate $Q_l = 1 \mu l/min$. The arrow indicates flow direction. b) Measured bubble decompression profile along the channel. $A_0$ is the reference bubble area at the channel entrance.