TUNABLE MICROFLUIDIC BUBBLE GENERATOR

Piotr Garstecki[1], Howard A. Stone[2], George M. Whitesides[1]
[1] Department of Chemistry and Chemical Biology, Harvard University 12 Oxford St., Cambridge, MA, U.S.A.

[2] Division of Engineering and Applied Sciences, Harvard University 29 Oxford St., Cambridge, MA, U.S.A.

Abstract

We describe a microfluidic flow-focusing device, and report: i) stable formation of monodisperse, micron scale bubbles, with an independent control over their size and volume fraction in the continuous phase, ii) dynamic behavior exhibiting period doubling and transition to chaos, and iii) dynamic formation of ordered arrays of bubbles. We present a quantitative analysis of breakup and explain the mechanism underlying the narrow size distribution of bubbles or droplets formed in a flow-focusing geometry.

Background

Several techniques for formation of micron scale droplets have been proposed within the last decade – from a shear rupturing technique [1], breakup in a co-flowing stream [2], to microfluidic systems [3-5]. Our study falls into a particularly important focus of work during recent years – the idea of a lab-on-a-chip and exercising precise control of microscale multiphase flows with an emphasis on formation of discrete fluid segments, with size, shape, and concentration independently manipulated.

Experimental

The microfluidic device used in our study is presented in Figure 1a. It was fabricated in PDMS using standard photolithography techniques[6]. We use nitrogen as the gas phase and aqueous solutions of glycerol with the addition of Tween20 surfactant as the liquid. At the end of the middle channel, upstream of the orifice, the liquid and gas phases form an interface. The pressure drop forces the tip of the gas ligament into the orifice where it assumes an unstable, cylindrical, morphology and periodically breaks to release bubbles into the outlet channel. In order to determine the mechanism of break-up we varied viscosity of the liquid μ, surface tension γ, geometry of the device and pressures applied to the system.

Results

We find that i) the volume V_b of the bubbles scales with the flow-rate q and the viscosity μ of the liquid, and the pressure p of the gas stream as $V_b \propto p/q\mu$ (Fig. 1c), ii) the rate at which the diameter of the gaseous thread decays in time during a single breakup event is linearly proportional to the rate of flow of the continuous liquid and is independent of the viscosity and surface tension (Fig. 1d). The first observation leads to the ability to control the size of the bubbles ($\propto p/q$) independently of the volume fraction of the dispersed phase ($\propto pq$). The second observation forms the basis of a controlled capillary instability mechanism, in which the rate of collapse of the unstable thread is greatly slowed down by the effect of confinement of the orifice and relaxation of the surface energy proceeds at the rate of supply of the continuous fluid.

As the bubbles are released at the orifice they are carried away by the liquid flowing in the outlet channel. The bubbles interact both directly by elastic shape-restoring forces when colliding with each other and indirectly by affecting the liquid flow field. The extent of order in the outlet channel is determined by the gas volume fraction ϕ. As ϕ approaches the value of surface coverage for a two-dimensional closed-packed lattice the bubbles self-assemble into ordered, flowing lattices. The repeat unit and geometry of the lattice depends on the ratio of the bubble radius to the outlet channel width. The characteristics of the ordered bubble structures can be tuned adjusting the pressures applied to the inlet channels. Few examples of flowing lattices formed in our devices are shown in Figure 1e.

Conclusions

The bubbles produced in the flow focusing devices are almost ideally uniform in size. A single orifice device produces up to several thousand bubbles per second. The volume fraction of the dispersed phase can be tuned and can approach almost unity (foams). Adjustable lattices of micron size bubbles or droplets can be integrated with other microfluidic or MEMS devices. As such, the tunable, flowing, lattices could become a new element of the lab-on-a-chip toolbox.

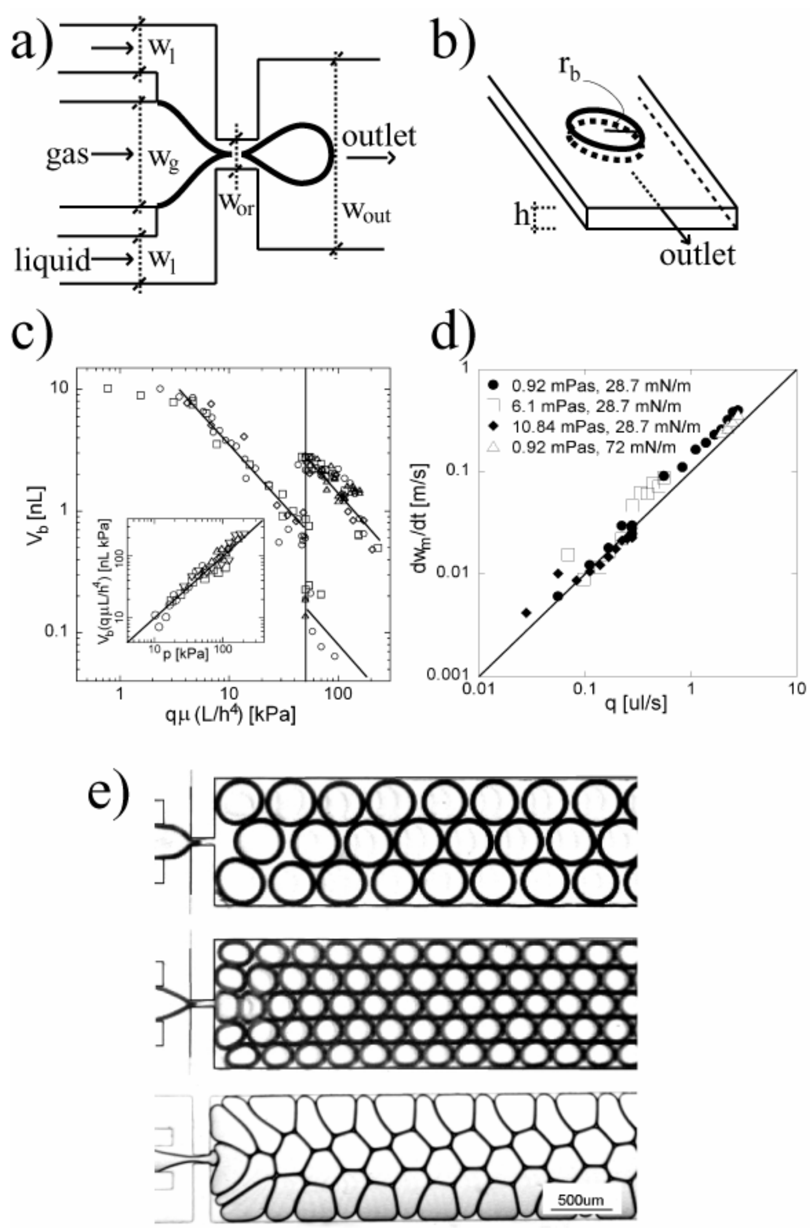

Figure 1. a) Schematic illustration of the microfluidic flow-focusing device (top view). The channels are uniform in depth. b) A schematic illustration of a bubble in the outlet channel. c) Scaling of the volume of the bubbles with the pressure applied to the gas stream, and rate of flow and viscosity of the continuous fluid. d) the rate of collapse (dw/dt), where w is the width of the collapsing thread, as a function of the rate of flow of the continuous fluid. e) Micrographs of dynamically assembled ordered lattices. The structure of the array depends on the ration of the size of the bubble to the channel width and on the volume fraction of the dispersed phase.

References

[1] Mason TG, Bibette J, Langmuir 13, 4600 (1997)
[2] Umbanhowar PB, Prasad V, Weitz DA, Langmuir 16, 347 (2000)
[3] Thorsen T, Roberts RW, Arnold FH, Quake SR, Physical Review Letters 86, 4163 (2001)
[4] Sugiura S, Nakajima M, Iwamoto S, Seki M, Langmuir 17, 5562 (2001)
[5] Anna SL, Bontoux N, Stone HA, Applied Physics Letters 82, 364 (2003)
[6] Whitesides GM, Xia YN, Angewandte Chemie International Edition, 37, 551 (1998)