Supplementary Material – Capture of colloidal particles by a moving microfluidic bubble

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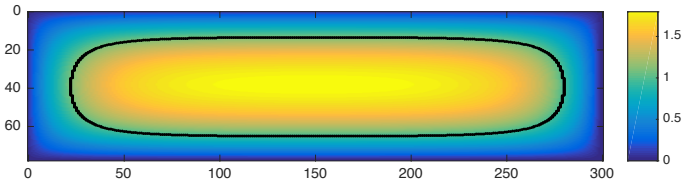
I. SUPPLEMENTARY FIGURES

A. Flow profile in the absence of a bubble

The flow profile in a microfluidic channel with a rectangular cross-section is given by [1]:

$$v(y,x) = \frac{4h^2\Delta p}{\pi^3 \eta L} \sum_{n \text{ odd}}^{\infty} \frac{1}{n^3} \left[1 - \frac{\cosh\left(n\pi \frac{y}{h}\right)}{\cosh\left(n\pi \frac{w}{2h}\right)}\right] \sin\left(n\pi \frac{z}{h}\right) \tag{1}$$

where the flow is in the x direction, h is the channel height (along z), w its width (along y), and $h < w$. In our experiments, $h = 78$ μm and $w = 300$ μm in the coating channel. The flow was computed numerically using MATLAB, where the sum was truncated after the first hundred terms. The resulting flow profile is shown in Supp. Fig. 1, where the flow speed was renormalized by the average flow velocity. In the coating channel, the maximum fluid velocity was 1.8 times larger than the average flow velocity. The colloidal solution flowed faster than the average flow speed in a central region of the channel covering more than half of the channel cross-sectional area, see the black line in Supp. Fig. 1.



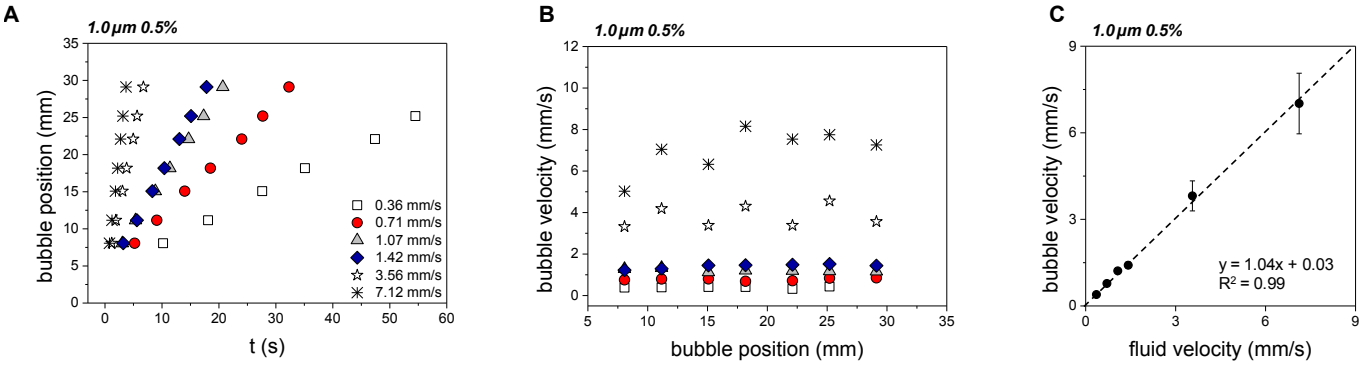
Supp. Fig. 1. Flow profile in the coating channel, in the absence of a bubble. Flow speeds are renormalized by the mean flow speed. All particles within the area delimited by the black line flow faster than the average flow speed.

B. Bubble speed in the coating channel

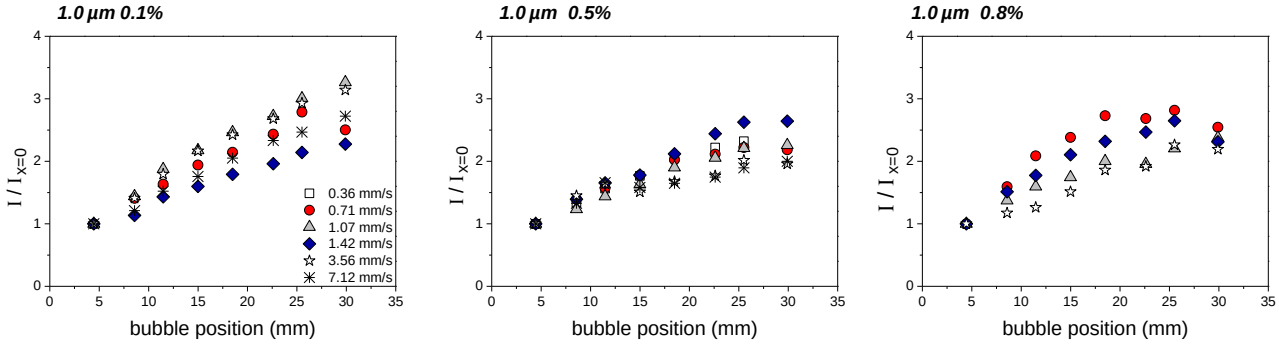
The bubble was tracked as a function of time, see Supp. Fig. 2A, and its speed was evaluated at 8 different positions, see Supp. Fig. 2B. To the precision of our measurements, the bubble speed was constant in the coating channel, and equal to the mean flow speed, see Supp. Fig. 2C.

C. Coating

The evolution of the bubble surface coverage with position in the coating channel is qualitatively similar for all bead sizes. Graphs in Supp. Fig. 3 show the evolution of the average fluorescence intensity of the bubble interface, a proxy for surface coverage, at 8 different positions along the coating channel, for 1 μm beads at different concentrations, and different flow speeds. The fluorescence increases with the bubble position, eventually reaching a plateau towards the end of the coating channel, an indication of crowding at the interface. Results are similar for or 0.5 μm and 4.5 μm beads, see Supp. Fig. 4



Supp. Fig. 2. A - Bubble position in channel as a function of time, for different speeds of the colloidal solution. B - Bubble speed as a function of position in the coating channel. C - Bubble speed as a function of the mean flow speed.



Supp. Fig. 3. Evolution of the coverage of the bubble interface, at 8 different positions in the coating channel, and for varying flow speeds. Three different concentrations of 1.0 μm particles were used: 0.1 wt%, 0.5 wt% and 0.8 wt%.

D. Estimating the fraction of beads captured by the bubble

As fluorescent colloids are captured by the moving bubble, the fluorescence intensity I_d downstream of the bubble is smaller than the fluorescence intensity I_u upstream of the bubble, see kymograph in Supp. Fig. 5. The ratio $\phi = (I_u - I_d)/I_u$ is a measure of the amount of colloids adsorbed at the interface.

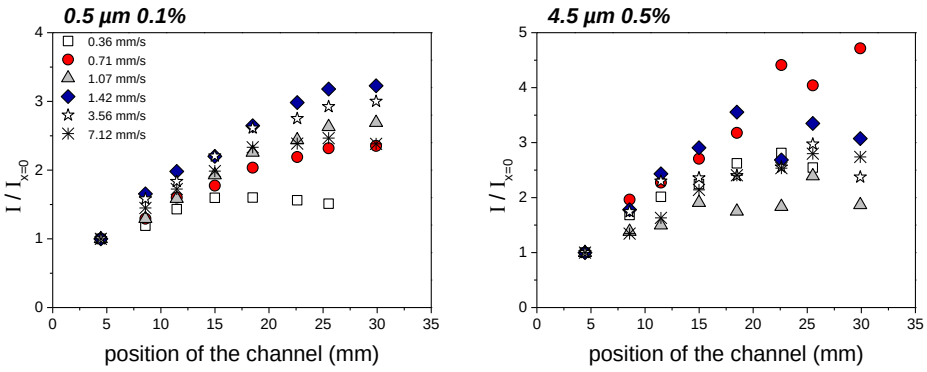
E. Estimating the surface coverage

At the end of the coating channel, the bubble was released in a conical observation chamber and adopted a spherical shape. The interface coverage was estimated by increasing the pressure in the chamber in a stepwise manner [2]. At each pressure increase, gas was transferred from the bubble into the bulk, leading to a shrinkage of the bubble. As the bubble radius decreased, the distance between adsorbed particles at the interface became smaller, until particles jammed for a small enough bubble radius, see Supp. Fig. 6. The surface area of the bubble before pressure increase is called A_0 and its surface area at the jamming transition is A_f.

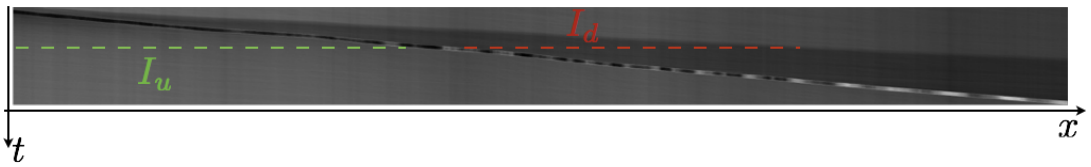
II. SUPPLEMENTARY MOVIES

A. Beads flowing around a bubble

Zooming in on a bubble shows that colloidal particles in the central region of the channel catch up with the back of the bubble and are diverted towards the gutters at the side of the bubble, see Supp. Movies 1 and 2. Both movies were shot under the same experimental conditions: a colloidal suspension of 1 μm beads at a concentration of 0.5 wt.%



Supp. Fig. 4. Evolution of the coverage of the bubble interface, at 8 different positions in the coating channel, and for varying flow speeds. Two bead sizes were used, 0.5 μm and 4.5 μm.



Supp. Fig. 5. Kymograph of an experiment, with the definition of the fluorescence intensities I_d and I_u, respectively downstream and upstream of the bubble.

was flowed through the channel at a mean flow speed of 0.71 mm/s. The scale is given by the coating channel width $w = 300$ μm.

B. Unwanted effects at high colloidal concentrations

At high colloidal concentrations, the bubble coverage increased up to a point where two unwanted effects could occur: bubbles could become stuck within the coating channel because of the no-slip condition between the coating colloids and the walls of the microfluidic device. Occasionally a stuck bubble could break into two bubbles as already reported in [3, 4]. Pictures of a stuck bubble and of a bubble breaking are shown on Supp. Fig. 7, where the colloidal suspension consisted of 0.5 μm beads at 0.5 wt.% concentration. The flow speeds were 0.71 mm/s and 7.1 mm/s in Supp. Fig. 7a and b, respectively. See also Supp. Movies 3 and 4.

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[3] Farzam Zoueshtiagh, Michael Baudoin, and David Guerrin. Capillary tube wetting induced by particles: towards armoured bubbles tailoring. *Soft matter*, 10(47):9403–9412, 2014.
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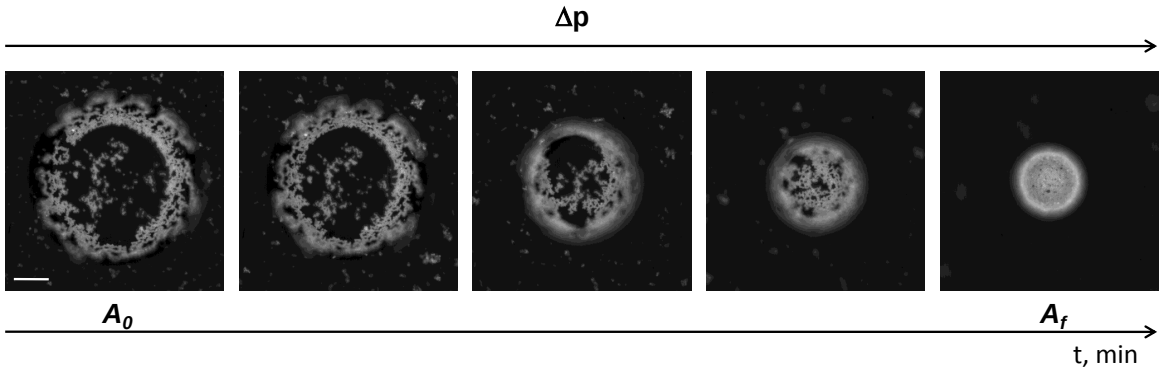
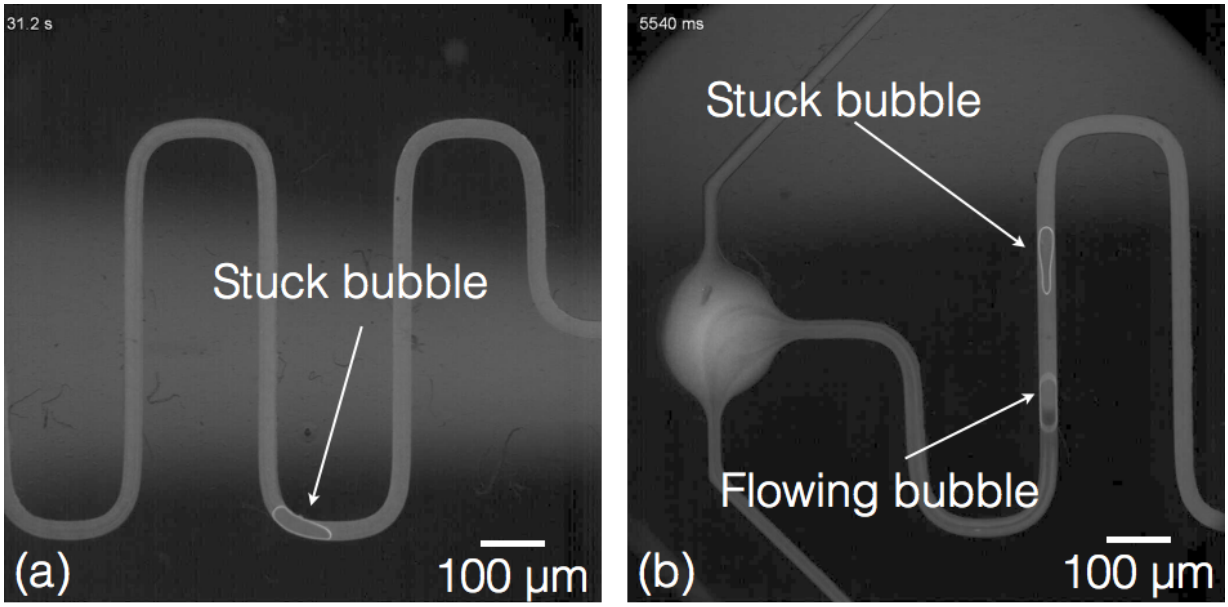


Supp. Fig. 6. Bubble in the observation chamber. The pressure in the chamber is increased step-wise, leading to bubble shrinkage and eventually jamming of the adsorbed particles on the interface. Particles: 4.5 μm, 0.5 wt.%. Flow speed used in the coating chamber: U = 7.12 mm/s. Scale bar: 100 μm.



Supp. Fig. 7. Colloidal suspension of 0.5 μm beads at 0.5 wt.% concentration. (a) Flow speed: 0.71 mm/s. The bubble becomes stuck in the coating channel because of the no-slip condition between the coating colloids and the microchannel. (b) Flow speed: 7.1 mm/s. The bubble becomes stuck in the coating channel and breaks into two, one of which flows away. See also Supp. Movies 3 and 4.