



## Microfoam formation in a capillary

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The ultrasound-induced formation of bubble clusters may be of interest for the manufacture of microfoths. We analyse how lipid-encapsulated microbubble clusters are formed in a cellulose capillary (Fig. 1) and what happens to the clusters if sonication is continued, using continuous driving frequencies in the range 1-10 MHz, using high-speed photography.

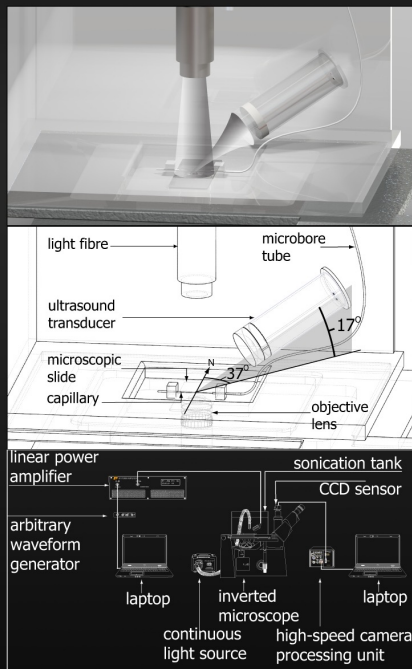


Fig. 1: Experimental setup. Internal dimensions of the container are  $24 \times 18 \times 15$  (cm)<sup>3</sup>.

We demonstrate that as soon as the bubble clusters are formed (Fig. 2) and as long as they are in the sound field, they behave as one entity (Fig. 3).

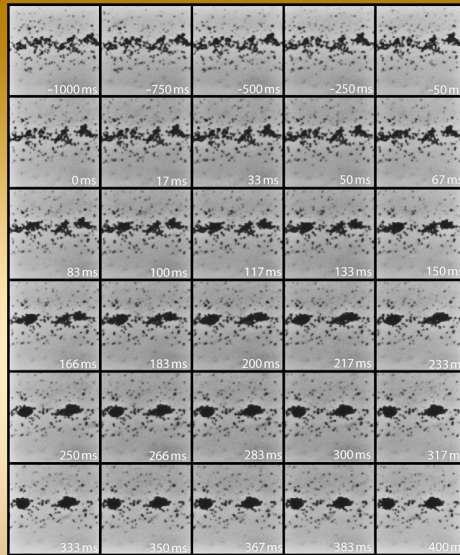


Fig. 2: Microfoam formation during continuous sonication at 2-MHz and 20 kPa peak-negative acoustic pressure. Each frame corresponds to a  $120 \times 120$  ( $\mu\text{m}$ )<sup>2</sup>

At our acoustic settings, it takes seconds to force the bubble clusters to positions approximately a quarter wavelength apart (Fig. 4). It also just takes seconds to drive the clusters towards the capillary wall (Fig. 5).

The following stages of microfoth formation are observed within a dense population of microbubbles before ultrasound arrival (Fig. 6). After the sonication starts, the lipid-encapsulated microbubbles collide, forming small clusters, owing to secondary radiation forces<sup>†</sup>. These clusters coalesce within the space of a quarter of the ultrasonic wavelength, owing to primary radiation forces. The resulting microfoths translate in the direction of the ultrasound field, hitting the capillary wall, also owing to primary radiation forces<sup>‡</sup>.

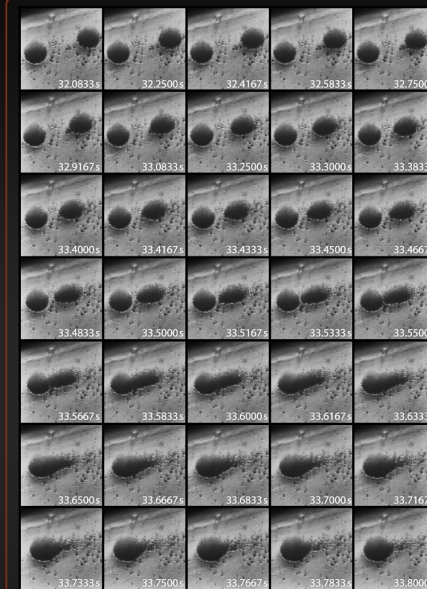
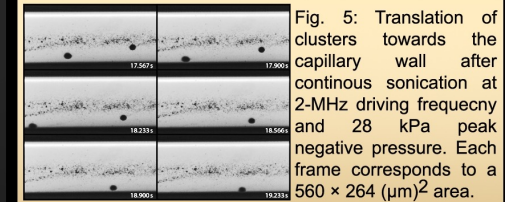
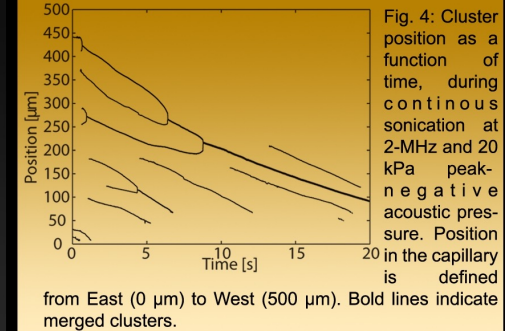


Fig. 3: Two clusters colliding and coalescing during continuous sonication at a 2-MHz driving frequency and a 20-kPa peak negative pressure. Each frame corresponds to a  $120 \times 120$  ( $\mu\text{m}$ )<sup>2</sup> area.



Subjecting lipid-encapsulated microbubbles of given concentration to a continuous low-amplitude signal makes it cluster to a microfoth of known position and known size, allowing for sonic manipulation.

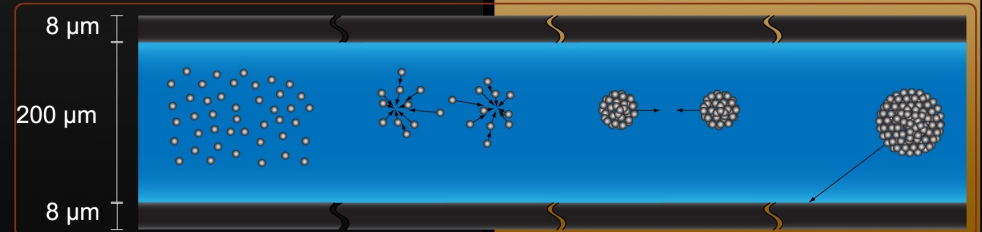


Fig. 6: Schematic representation of the four stages of microfoam formation in a capillary: (left-right) random bubble distribution before ultrasound arrival, bubbles colliding during sonication, cluster coalescing within the space of a quarter of the wavelength, microfoam translation.

$$\dagger u \approx -\frac{(2\pi f p_0)^2}{27\eta} \rho \kappa^2 \frac{R_0^5}{d^2}$$

$$\ddagger v \approx \frac{p_0^2}{6\rho c f} \left[ \left( \frac{f}{f_c} \right)^2 - 1 \right] + \left[ \delta \left( \frac{f}{f_c} \right) \right]^2$$

$c$  – speed of sound  
 $d$  – bubble distance  
 $f$  – driving frequency  
 $f_c$  – cluster resonance frequency  
 $p_0$  – peak acoustic pressure  
 $R_0$  – equilibrium bubble radius  
 $u$  – approach velocity  
 $v$  – translational velocity  
 $\delta$  – total damping coefficient  
 $\eta$  – shear viscosity  
 $\kappa$  – bubble compressibility  
 $\rho$  – fluid density