Surface cleaning by soft acoustic cavitation bubbles

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Introduction

Surface cleaning by cavitation is a well known phenomenon [1]. Typically, it is associated with high-intensity ultrasound generating and driving the bubbles. Accordingly, strong bubble collapse events are as well typical for standard ultrasonic cleaning, and in many cases this "hard" or "transient" cavitation is desired for efficient cleaning. Damage and erosion of material can be an accompanying effect, apparently caused by just the same violent bubble collapse events. Additionally, there are recent reports on cleaning by "soft" acoustic bubbles, i.e. weakly or moderately driven bubbles attached or close to surfaces [2, 3, 4]. Such type of ultrasonic cleaning seems especially suited for microscopic particulate contaminations of sensitive surfaces, e.g. for cleaning purposes in the semiconductor industry. For utilisation in such cleaning processes, the understanding of the contaminating particle adhesion to the substrate and the possible forces applied by the cleaning mechanisms and their order of magnitude is crucial [5]. However, the naive relation of creating a heavy collapse (usually related to jetting) that subsequently leads to cleaning is not valid or useful in these soft bubble cases, like in erosion studies [6]. The softbubbles typically do not undergo strong volume oscillations or heavy collapses, which points to different cleaning mechanisms than those being associated with hard cavitation (i.e. jetting and shock wave emission). Here, a report is given on some experimental observations of weakly driven acoustic bubbles at a glass substrate. In particular, the phenomena due to motion of the three–phase boundary (contact line) are closer investigated and discussed with respect to particle removal.

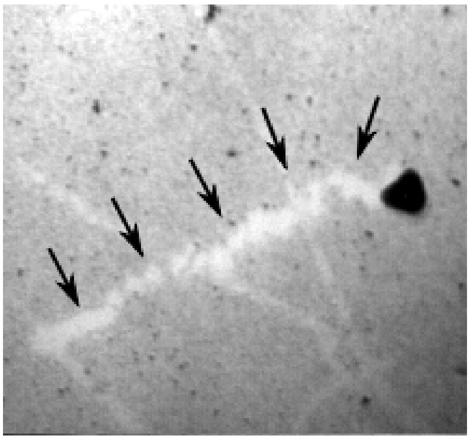

Figure 1: A bubble, driven at 230 kHz, with surface mode (n=3) leaves a cleaned trace (arrows) on a coated glass slide (1 µm melamine resin particles). Exposure time is 6.5 µs.

Observations

As contaminant we used melamine resin spheres of 1 µm and 10 µm diameter. For sonication, standard piezo ceramics glued to the system or alternatively a sonotrode were used in the regime of some 10 kHz with amplitudes small enough to inhibit transient cavitation. Imaging is achieved with a high–speed camera (Photron FASTCAM SA5) attached to a long–distance microscope (K2, Infinity) or to an inverted microscope (Nikon Eclipse Ti). Several possible mechanisms of cleaning by the bubbles have been identified. Figure 1 shows an example of cleaning by an attached moving bubble.

Flow around oscillating bubbles:

The presence of a rigid boundary next to the oscillating bubble will result in a time averaged non–zero flow [7] as shown for two examples in Fig. 2. Furthermore, during a bubble's oscillation its moving liquid–gas–interface induces a periodic inward and outward flow that, near the bubble, by far supersedes the acoustic wave velocity. This wobbling motion seems to be able to additionally act somehow fatiguing to the bonding between contamination and substrate. The flow around attached bubbles has been observed to detach adhered particles, even without direct contact of the bubble with the particles (not shown here).

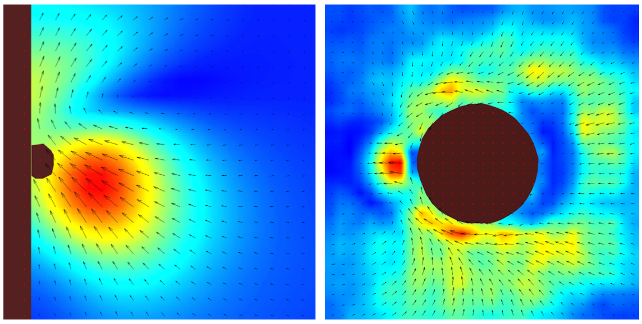

Figure 2: Colour–coded [8] net flow $\leq 1\,{}^{\mathrm{cm}}/_{\mathrm{s}}$; red (fast) and blue (slow). Left: A 100 µm bubble attached to a vertical glass slide and driven at 46.2 KHz with surface modes is creating an upwards flow (raw data by Xɪ [9]). Right: Top view of an attached 130 µm bubble driven at 21 kHz with volume oscillations creating a left–directed flow.

Attractive property of the bubble–wall

Depending on the properties of the contamination, the bubble–wall may attract and bond contamination to it (see Fig. 3). Consecutively, such bubbles can detach and transport loosened contamination away from the area to be cleaned. No complete contact line sweeping over the adhered particles has been observed here.

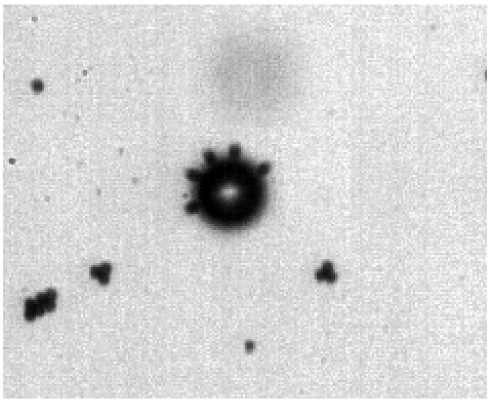

Figure 3: A bubble "collects" 10 µm melamine resin particles on its surface as it performs volume oscillations and moves over the glass slide.

Capillary meniscus

Contact lines, advancing or receding completely over particulate contamination, might show a high curvature resulting in a quite high capillary force due to surface tension (see Fig. 4). The liquid interface can render a rubber–like behaviour by winding itself around the contamination, pulling on it and (if sufficiently strong) eventually removing it (not happening in Fig. 4 but observed in other cases).

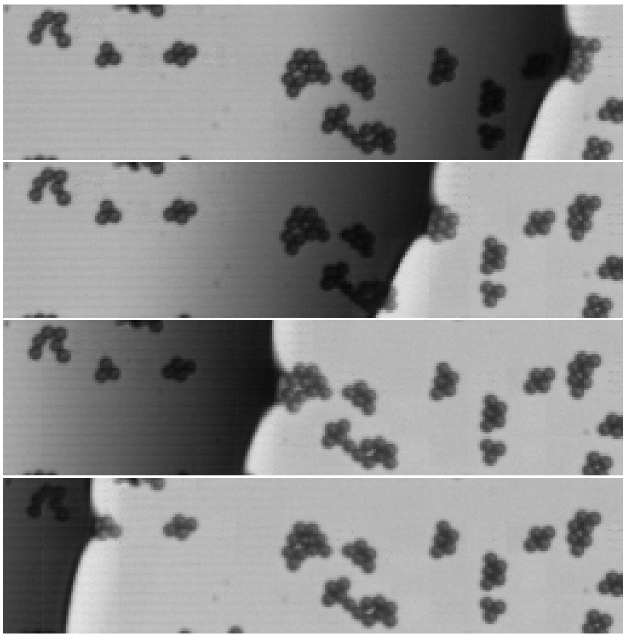

Figure 4: A contact line, which is generated with a syringe between two glass slides, recedes (approx. 4 cm/s) over 10 µm melamine resin particles and gives rise to a "pulling" force.

Moving interface with advected material

It is observed that under similar conditions the cleaning efficiency of a moving contact line increases if debris (loosened particles) is present within the contact line, cfr. "Jamming" (see Fig. 5). The presence of some obstructing material effectively increases the viscosity of the liquid and therefore the exerted shear stress — similar to a river during winter being capable of destroying bridges due to many floating ice floes. Counter-intuitively, the idea of cleaning with a "dirty" solution holds interesting aspects. Of course, one has to consider that this additive should be removed as well, e.g. by using a dissolving or a non–residue one.

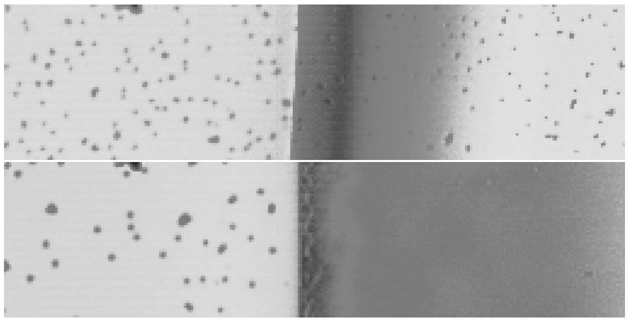

Figure 5: A contact line, which is generated with a syringe between two glass slides, advances (approx. 1 cm/s) from right to left over 10 µm melamine resin particles. In contrast to the upper image, the lower image shows a contact line that includes debris (loosened particles) and removes all particulate contamination present on the substrate.

Summary

The experiments reveal the diversity (although surely not all existing mechanisms) of the cleaning interaction between a "soft" bubble and a substrate with particle contamination. Cleaning does not necessarily involve erosive bubble collapse. Most likely the three–phase boundary then plays the key–role. Utilizing its potential is not yet sufficiently done and still far away from being fully understood. Its individual aspects like capillary force, rubber–like property, jamming, and bonding of contamination to it, have to be further investigated and properly combined to gain the best results. Although a net flow in the vicinity of an oscillating bubble might not be capable of removing very sticky contamination (since the exerted shear flows are too weak in the case of mild cavitation), its oscillatory component might contribute to loosening by steadily fatiguing the bond of the contamination with the substrate.
As these processes are somehow related to the acoustic irradiation into the system, the proper threshold for each case needs to be found individually to prevent "hard" cavitation from eroding what has to be cleaned.

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