Exploring the mechanism of cleaning with soft cavitation bubbles

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Abstract

Cleaning of sensitive surfaces with cavitation bears the danger of damage, even at higher ultrasonic frequencies. Recently it has become clear that for micro- and nano-particulate contaminations also "soft" cavitation bubbles could be efficient cleaning agents: gently driven surface attached bubbles that do not undergo strong oscillations and collapse. Here the motion of the three-phase boundary (contact line) plays a crucial role, and we designed a micro-flow channel to explore in more detail its cleaning power. At the same time, a standard method for measurement of stickiness of particles should be developed. We present first results and comparison to flow simulations. Preliminary observations show enhanced cleaning by an avalanche effect produced by looser particles carried in the flow and a large amount of particles stored in the air-water interface. This increases cleaning efficiency with flow velocity.

Introduction

Cavitation technology is very well known for cleaning surfaces. The development of these technologies has the problem to know the degree of adhesion of the particles attached on the sample surface. A standard scaled method to test this degree of attachment must be developed to be able to compare different methods to attach particles on surfaces and, therefore, be able to compare detaching forces.

It is known from environmental research that for colloids attached on a flat substrate, contact lines (bubbles and liquid fronts) have much more cleaning power than the liquid flow itself [1],[2],[3]. There seems to be an inverse relation between detachment power and the velocity of the contact line, reaching no particle cleaning for particles under too fast flow contact lines; i.e. faster than 0.15 m/s in the case of Gomez Suárez et al. (1999) [3]. This is a complex phenomenon which is not yet fully understood. It depends on parameters like particle size, direction (air-liquid or liquid-air) and speed of contact line, contact angles of the liquid on particles and substrates, and possibly others like particle shape or charges. Besides these complex agents affecting the cleaning power of advancing and receding contact lines, in the cases of relatively dense contamination, a certain avalanche effect plays a role: transported loose particles accumulate in the contact line and can expel other particles. This effect may be stronger and simpler to control in an experiment.

Strongly oscillating and collapsing cavitation bubbles can loosen particles by jet impact and/or acoustic shock waves but these phenomena can also erode and structurally damage the material of the surface. Recently it has been found that "soft" cavitation bubbles in close contact with a solid substrate are also able to clean substrates [4],[5]. Soft cavitation bubbles do not undergo strong oscillations —they merely pulsate weakly— therefore they are gentle with the surfaces. Thus, removal of particle contamination on sensitive substrates without damage might be feasible.

Here we expose two types of experiments. Experiment 1 demonstrates cleaning with soft cavitating bubbles. Experiment 2 explores particle removal by moving three-phase boundaries (contact lines) in a micro-flow channel; both, of the first water front and of subsequent bubbles.

Materials and methods

For both experiments we used a high-speed camera (Photron) and melamine resin particles (Fluka). For experiment 1 we built a small receptacle using a standard microscope glass slide as base and gluing pieces of other glass slides on it as walls. We also glued a small piezo-transducer at a side of the base slide and deposited 10 µm particles on the base of the receptacle. Then the device was filled with water and sealed with another glass slide. With the piezo-transducer we generated micro-bubbles oscillating at 20 kHz.

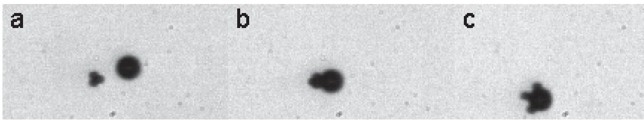

Figure 1: Experiment 1. (a): Bubble driven at 20 kHz, attached to the glass and drifting towards a cluster of three particles. (b): Contact and detachment of particles. (c): The particles are de-clustered, stuck to the bubble surface and are transported with the bubble.

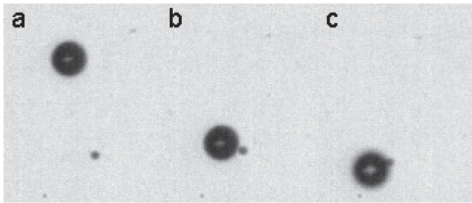

Figure 2: Experiment 1. (a): Bubble driven at 20 kHz and attached to the glass drifts downwards and attracts a particle by micro-streaming without being in direct contact before detachment. (b): The particle sticks to the bubble wall and is transported along with it (c).

In experiment 2 we used 6 µm particles (stock solution diluted to 1:200 and 1:2000 in DI water) deposited on microscope glass slides. To achieve a homogeneous distribution of particles, the particle solution is poured over a slide prepared on a spin-coater and is immediately spun. The slides where fixed to a micro-flow chamber (Ibidi) with a pressing cell of our design. We used a syringe pump to generate an average flow velocity of 0.70 m/s. The liquids we used were DI water and DI water with soap. For these settings, simulations predict 1D-Poiseuille flow; which is confirmed by particle trajectories. We introduced air bubbles in the liquid flow to be able to compare the effect of the first front wave and subsequent contact lines (bubbles).

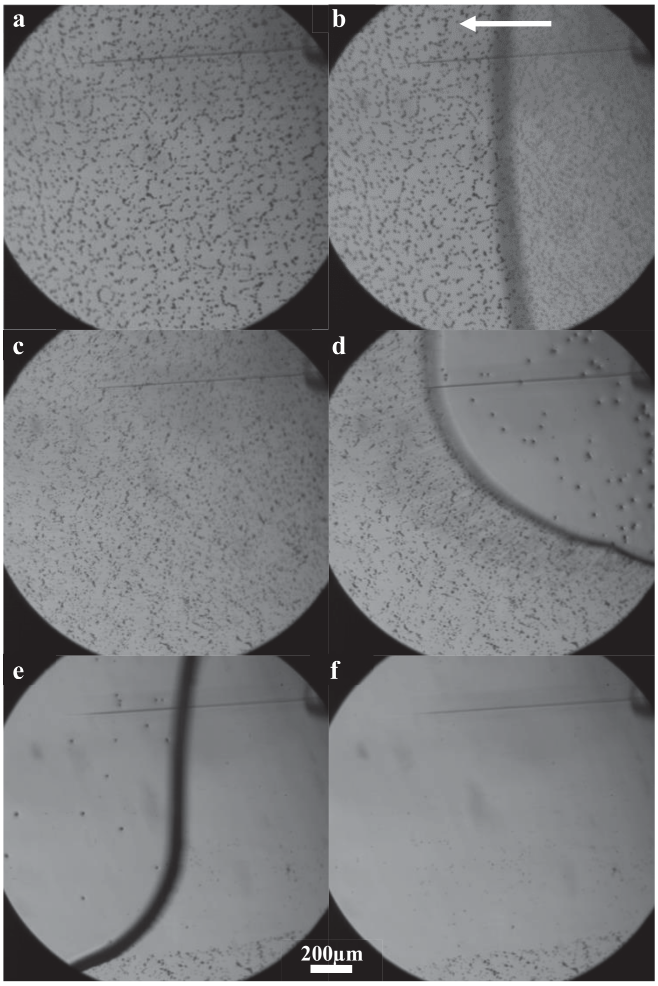

Figure 3: Experiment 2. Flow in the direction of the arrow (inset in (b)). (a): Dry particles attached to a glass slide. (b): Water meniscus entering and passing over the particles. (c): Particles covered by water; many particles flowing with the liquid, but some particles still attached. (d): Air bubble passing (gas to the right) and washing additional particles away. (e): End of air bubble (gas to the left): The second air-water transition again detaches particles and leaves an almost clean area. (f): View of the difference in particle removal achieved with or without air bubble (stripe on the bottom).

Results and discussion

Experiments show that contact lines can clean by a variety of contact line-particle interactions. Experiment 1 demonstrates cleaning by soft cavitation bubbles driven on a surface (Figures 1 and 2). With respect to substrate integrity, it has to be pointed out that soft cavitation bubbles do not involve acoustic shock waves or high-speed jet flows, which are both candidates for material erosion and structure damage.

Preliminary results of experiment 2 suggest enhanced particle cleaning due to the avalanche effect started by lose particles accumulating in the contact lines of the first advancing water front and bubbles (Figures 3 and 4). Bubbles are more effective cleaners than the water front as long as they carry enough particles in their contact lines. Late coming bubbles have no effect on particle cleaning when not carrying particles in the contact lines. Short exposure to a flow of soaped water foam does also not increase cleaning. However, we suspect that longer exposures to it may have a cleaning effect due to fatigue of particle adhesive bonding. Soaped water contact lines tend to clean more than those of DI water, suggesting that a decrease in surface tension of water increases cleaning.

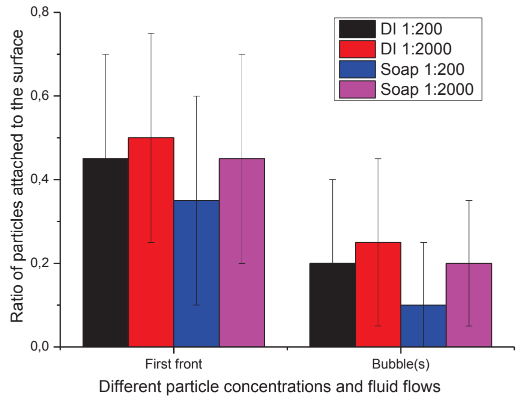

Figure 4: Ratio of particles still attached to the glass slide after the action of the first front and after subsequent bubbles loaded with particles. 1:200 and 1:2000 indicate slides contaminated with particle solutions diluted to this concentrations from stock solution. DI indicates the fluid was just DI water. Soap indicates the fluid was DI water with soap.

In conclusion, the quite promising potential of contact lines and "soft" cavitation bubbles for gentle particle detachment still needs to be explored in more depth, as various phenomena and parameters (like oscillating flows and fatigue, speed of contact lines, avalanche effects etc.) appear to significantly influence the process.

Acknowledgements: The financial support by the Austrian Federal Ministry of Economy, Family and Youth and the National Foundation for Research, Technology and Development is gratefully acknowledged.

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