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Physical forces exerted by microbubbles on a surface in a traveling wave field

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ABSTRACT

The effect of a wave with a varying traveling component on the bubble activity as well as the physical force generated by microbubbles on a surface has been studied. The acoustic emission from a collection of bubbles is measured in a 928 kHz sound field. Particle removal tests on a surface, which actually measures the applied physical force by the bubbles on that surface, indicate a very strong dependence on the angle of incidence. In other words, when the traveling wave component is maximized, the average physical force applied by microbubbles reaches a maximum. Almost complete particle removal for 78 nm silica particles was obtained for a traveling wave, while particle removal efficiency was reduced to only a few percent when a standing wave was applied. This increase in particle removal for a traveling wave is probably caused by a decrease in bubble trapping at nodes and antinodes in a standing wave field.

1. Introduction

The behavior of a single isolated bubble in a sound field and even the interaction of a single bubble with a surface are very well understood. A lot of experimental and theoretical work has resulted in an in-depth understanding of bubble oscillations and even the asymmetric bubble collapse has been elucidated. Very often, Rayleigh–Plesset type of equations are able to reproduce the main bubble effects [1,2]. The behavior of bubble clouds is being studied, but a thorough understanding of multi-bubble systems is still lacking [3–6]. This multi-bubble behavior is important since most applications rely on the global effect of a multitude of bubbles and very often, the interaction of a bubble cloud with a surface needs to be controlled. The applications range from the production of nano-particles [7] over the treatment of cancer cells [8] towards the cleaning of complicated 3 dimensional structures [9] or even fragile nanometer sized structures [10]. Most of the high end applications require a precise control over the number of bubbles, bubble size distributions, bubble–bubble and bubble-surface interactions. All these factors will influence the efficiency of the targeted application. A precise control is even more important when the allowed physical forces exerted on a surface are limited to a small process window [11]. An excellent control over the physical forces exerted by the bubbles on the surface is therefore extremely important. A multitude of physical phenomena, which include Schlichting or boundary layer streaming [12,13], microstreaming [14], water hammer force due to bubble collapse [15] and even the possible formation of shock waves [16], are responsible for the physical forces acting on a surface. All these effects depend on the sound field and as a result, a precise control of the sound field will be necessary to reach the level of control which is necessary for the high end applications. However, sound reflections are often not well controlled in real life applications. Thiemann et al. [17] investigated a focussed standing wave with a share of a traveling wave away from the transducer. It was observed that bigger bubbles were trapped in nodes parallel to the transducer, while smaller bubbles (so called streamers) showed a fast movement away from the transducer.

Here, we will show that acoustic reflections will have a large influence on the physical force exerted by microbubbles on a surface. The use of anechoic materials together with careful positioning of the treated object, allows to maximize the traveling component of the sound field. It is shown that this can dramatically improve the particle removal process efficiency.

2. Experimental setup

A PVDF cleaning tank with liquid volume of ~65 l has been used. A diagram of the setup is shown in Fig. 1. The tank is equipped with a 928 kHz flat transducer positioned at a side wall

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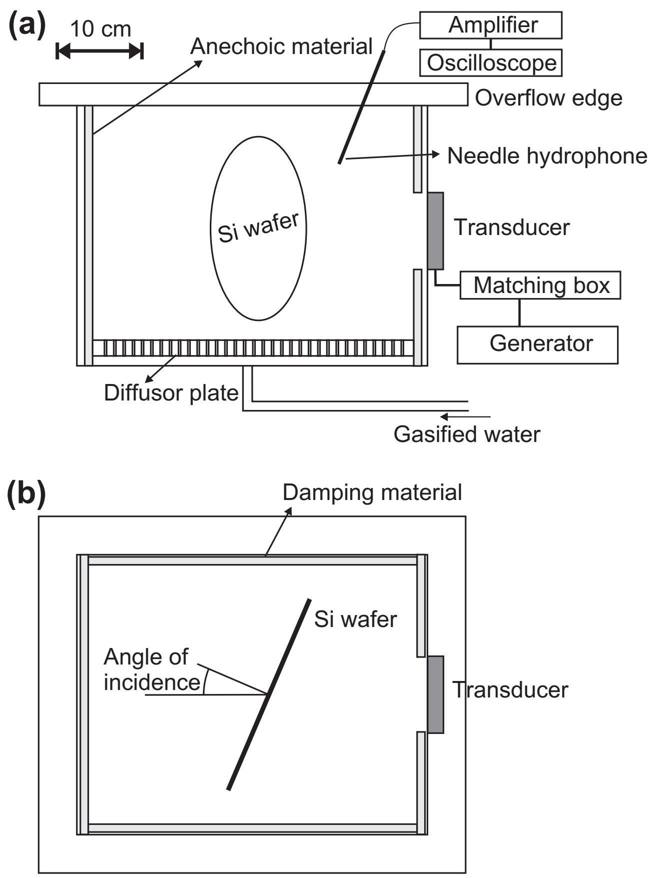

Fig. 1. A diagram of the acoustic cleaning system. Image (a) shows the side view of the system and image (b) is a top view of the setup.

with an active area of 59.6 cm^2. The transducer is driven with electronics of Prosys Inc., which are capable of pulsing the acoustic field. For each pulse period, the pulse on time (T_{on}) and pulse off time (T_{off}) can be varied, as long as the duty cycle ($T_{on}/(T_{on} + T_{off})$) is between 10% and 90%. The system is hooked up to a 'gasification system' that first degasses the liquid before the liquid is gasified in a controlled manner with membrane contactors (Phasor II, Entegris) [10]. The liquid is gasified with oxygen and the dissolved oxygen content is measured with a dissolved oxygen probe (Oakton DO600) based on a galvanic measuring element. A diffuser is placed at the bottom of the cleaning tank in order to optimize flow uniformity inside the tank. A flow controller is installed in order to stabilize the liquid flow rate around 28 l/min. This flow rate results in a tank refresh time of 2.3 min., which is chosen to prevent degassing of the liquid due to the applied ultrasound. The high flow rate requires the use of 3 degassing and 3 regassing membrane contactors in parallel. An anechoic material (Aptflex F28, Precision Acoustics) can be placed along the walls inside the cleaning tank.

3. Measurement techniques

The bubble activity which originates mainly from the bulk of the liquid is measured with a needle hydrophone with an aperture of 500 μm (Onda, HNR-500). The hydrophone is positioned outside the main sound beam. The sound signal is amplified with a home-built amplifier based on 'AD8066' fastFET op-amps (approximately 50 dB amplification, 5 MHz bandwidth) prior to being captured with an oscilloscope [18]. Each bubble in the sound field acts as a secondary sound emitter and the hydrophone measures the average signal over a large number of emissions from individual bubbles [1,19]. As a result, the hydrophone detects a complicated pressure oscillation, which is difficult to interpret directly. Therefore, the frequency components are usually measured to get an idea of the bubble oscillations. At very low pressure amplitudes, bubbles will oscillate linearly and only the fundamental frequency will be present in the spectrum. At higher pressure amplitudes, non-linear effects will appear due to the non-linear bubble oscillation, deviation from spherical motion, increase in bubble–bubble interaction... [1]. Therefore, the final spectrum is calculated via fast-fourier transformation of the recorded pressure signal.

To assess the nanoforce exerted by microbubbles on a surface, SiO_2 nanoparticles are deposited on a Si wafer. First, the 300 mm Si wafers are given an in-house clean [20]. In the first step an oxidant (sulfuric acid/ozone mixture) is used to remove the organic contaminants from the surface and to form a uniform oxide over the wafer. In the second step a HF based chemistry is used to remove the oxide. At the same time it lifts off the particles and dissolves the metals. After this step the surface is passivated again in ozonated DI water to grow a clean chemical oxide and the wafers are dried. The cleaned wafers are evaluated by measuring light scattering in the haze mode. Next, 78 nm SiO_2 particles are spin coated on top of the wafer with a particle density of $\sim 10^6$ particles/cm^2. The contaminated wafers are measured again by light scattering and aged for 24 h. This aging results in an increase of the particle–surface bonding force due to the formation of covalent bonds [21,22]. The removal force of the aged particles is in the order of 10 nN [11]. After the physical cleaning process, the wafers are analyzed again by light scattering, which gives us an overview of the areas where the particles are removed. In the cleaned areas, the physical force exerted by oscillating bubbles was higher than the adhesion force, while in the contaminated areas, the applied physical force was lower. As a result, the cleaning procedure of a deliberately contaminated wafer can be used as a nano pressure sensing device. Particle removal efficiency (*PRE*) values are extracted from the cleaning data as follows

$$PRE = \left(1 - \frac{\sigma_{after\ phys.\ clean} - \sigma_{before\ contam.}}{\sigma_{after\ contam.} - \sigma_{before\ contam.}}\right) \times 100\% \quad (1)$$

where σ denotes the particle surface concentration measured by light scattering [23].

4. Results

DI water is gasified to a 120% oxygen saturation level which corresponds to ~52 ppm of oxygen. This means that bubbles larger than 7.2 μm will grow while smaller bubbles will shrink continuously in the absence of an acoustic field [24]. This is because the Laplace overpressure is large enough for small bubbles to drive the gas out, even when the surrounding liquid is oversaturated [25]. The distance between the wafer and the transducer was 18.1 cm. The total pulse period is 333 ms and the duty cycle of the pulses is 25%. The latter parameters are chosen in order to maximize the bubble activity by keeping the average bubble size around its resonance radius [26,27]. A thorough explanation of the optimal parameters is given in [28]. The angle for which the wafer is transparent for the applied longitudinal pressure waves can be found experimentally by measuring the reflected power. For this measurement, the damping material at the opposite side of the transducer is removed. At the transmission angle of the Si wafer, sound waves travel through the wafer and are reflected at the tank wall. Next, sound waves travel again through the wafer in the opposite direction and influence the reflected power of the transducer driving signal [29]. The power reflected back into the transducer is measured and shows a maximum around the transmission angle (see Fig. 2). The reflected power is maximized by