A novel ultrasonic cavitation enhancer

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Abstract. We introduce a Cavitation Intensifying Bag as a versatile tool for acoustic cavitation control. The cavitation activity is spatially controlled by the modification of the inner surface of the bag with patterned pits of microscopic dimensions. We report on different measurements such as the transmission of ultrasound, temperature increase inside the bag during sonication. Several applications of interest to other scientific activities are also demonstrated.

1. Introduction

Ultrasonic cleaning relies on the formation and collapse of bubbles in the vicinity of the contaminated substrate. Recently, the different physical cleaning mechanisms involved when bubbles collapse have been discussed in a Special Issue of Ultrasonics Sonochemistry \cite{1}, but cavitation in general remains a stochastic process \cite{2}. Control over the cleaning process can be obtained by defining the location and instant that the bubbles appear, influencing the cavitation nucleation process. Artificially created microscopic pits act as source of ultrasonic cavitation nuclei \cite{3}, and can be used for cleaning \cite{4}. We introduce a three-dimensional way to bring cavitation near an arbitrary object in a controlled way, with the potential to enhance processes such as cleaning, sonochemistry \cite{5} and emulsification \cite{6}.

1.1. General description of the Cavitation Intensifying Bag

Plastic containers (hereafter named Cavitation Intensifying Bag or CIB) were modified to include pits in its inner surfaces. These CIB’s were designed and patented by two of the authors, and commercialised as BuBble Bag by BuBclean. When a liquid is poured inside (e.g. water, ethanol, acetone, surfactant solutions), a gas bubble can be trapped in the pits depending on the gas content of the liquid. Upon exposure to ultrasound, microbubbles are generated at the predefined locations and in large quantities. Using CIB reduces the amount of chemicals used for cleaning: typically 10–100 mL instead of 1–100 L for the entire ultrasonic bath, or other liquid containers (e.g. metal, glass). The bag furthermore assures that the contaminants removed during cleaning do not cross-contaminate other objects cleaned inside the ultrasonic bath, or contaminate the ultrasonic bath content itself. The thin plastic material transmits ultrasound better than metal or glass containers, which have a high reflection coefficient.
2. Characterisation of the CIB

2.1. Thermal conduction through the CIB wall

An ultrasonic bath (DT510H-RC, Bandelin) operating at 35 kHz was pre-heated to 53.0±1°C; three CIBs were filled with tap water at 21.5±1°C. One T-type thermocouple (Z2-T-2-MP, Labfacility) was immersed in the ultrasonic bath, additional thermocouples were fixed inside the CIBs. The CIBs were immersed in the bath and the thermocouple values were recorded during 4 minutes using a data logger (TC08, Pico Technology). With the ultrasound switched on, the liquid inside reaches the temperature of the ultrasonic bath in 2 minutes, whereas without ultrasound, the temperature was 5°C below the temperature of the ultrasonic bath at the end of the experiment (4 minutes). After 2 minutes, the temperature inside the CIB was 44°C.

2.2. Acoustic transmission through the CIB wall

The acoustic attenuation of the CIB walls was determined using a needle hydrophone (HNR-500, Onda) at one position. The hydrophone (not calibrated for 35 kHz) was connected to an oscilloscope (DPO 4034, Tektronix) recording 0.1 s of acoustic data at a rate of 12.5 MS/s and allowed for estimating the relative attenuation by the plastic wall material. The geometry and acoustic boundary conditions of the ultrasonic bath were recreated digitally in CFD software (COMSOL Multiphysics v5.0, COMSOL). The acoustic driving was modeled by 4 circular sources, equally distributed around the bottom of the bath, and driven at an amplitude of 0.34 µm, and a nominal frequency of 35 kHz changed sinusoidally with ±1 kHz every 1 ms (i.e. 100 Hz)[7]. A CIB was modelled as a shell, located inside the bath above one of the transducers, with standard material properties for the plastic material (PP). The CIB and the bath itself were filled with water at 30°C. The maximum element size was 8.6 mm, with finer mesh near the CIB. Each ultrasound period was discretised with 30 time steps and the total simulation time was 1.2 ms. The rms-value of the pressure at a frequency of 35 kHz was attenuated with 7.7%. The numerical simulations predicted that the pressure in the center of the CIB was 0.7% lower than the pressure at the same location above one of the other transducers. No phase difference was observed between the two evaluation points in the numerical model.

2.3. Visualisation of the cavitation activity

One transducer from an ultrasonic bath (P2000, Qtec; frequency: 42.7 kHz) was mounted inside a transparent bath (10 L of tap water at 21°C). A CIB was mounted in front of the transducer at a distance of approximately 5 cm. A high-speed camera (SA7, Photron) with a 50 mm lens (Zeiss) was positioned outside the tank to record the cavitation activity at a speed of 1000 fps, and light was provided using a flood light (Hella). For sonochemiluminescence imaging, a CIB was filled with a 2 mM Luminol and NaOH solution at pH 10 and fixed horizontally inside an ultrasonic bath (DT510H-RC, Bandelin) filled with tap water at 21°C. The ultrasonic bath was located inside a light-tight box, equipped with a remote-controlled photo camera (D300, Nikon; aperture f/1.8, shutter time 30s, ISO Hi1.0) and 50 mm lens (Nikkor). The sonochemiluminescence was recorded during 30 s of ultrasound exposure to the CIB. The high-speed recordings showed clusters of bubble originating from the pits inside the CIB (Figure 1a). Some of these bubble clusters were interacting and formed combined bubble clusters, similar to those reported elsewhere [4]. The long-exposure photographs showed sonochemiluminescence signal coming from within the CIB only, in a distinct pattern corresponding to the pits inside the CIB and interacting bubble clouds (Figure 1b).
Figure 1. (a) High-speed image showing bubble streamers (white spots indicated with yellow arrows) originating from the regular pattern of pits inside the CIB. (b) Blue zones recorded as a result of the chemical reaction of radicals produced by the cavitation bubbles and the Luminol solution in the CIB (sonochemiluminescence). The white lines indicate the outer dimensions of the CIB. The yellow bars represent 5 mm.

3. Demonstration of functioning and potential applications

3.1. Cleaning indicators and 3D printed parts

A Level 3 cleaning indicator (gke) was fixed inside a CIB to visualise the ultrasonic cleaning activity inside the ultrasonic bath filled with tap water at 21°C. The coloured side of the indicator, facing away from the transducer, was imaged with a camera (D5100, Nikon), and the removal of the cleaning indicator dye was monitored during ultrasound exposure. The dye removal occurred in a very specific ‘honeycomb’ pattern, corresponding to the locations of the pits in the opposite wall of the CIB. A Cleaning Challenge Device (CCD) [8] was printed in two-fold using a DLP 3D printer (S30L, RapidShape). The CCD represents a challenging 3D printed model from which support material needs to be removed. One CCD was cleaned using the standard protocol prescribed by the printer manufacturer (3 minutes in isopropylalcohol in the ultrasonic bath, followed by blowing with pressurised air and another 3 minutes of ultrasound). The second CCD was cleaned using the CIB filled with 50 mL of isopropylalcohol and placed for 1 minute in an ultrasonic bath filled with demiwater. It was found that the CCD treated in the CIB was cleaned in only 14% of the time needed for the first CCD.

3.2. Emulsion preparation

Hexadecane emulsions were made by pipetting 2.25 mL of hexadecane into a CIB containing 10 mL of 1% SDS aqueous solution to obtain oil hexadecane concentrations of about 15%. The CIB was placed for 60 minutes inside an ultrasonic bath (P60H, Elma; frequency: 80 kHz, amplitude: 100%) filled with 1/3 tap water and 2/3 demiwater at 21°C. The resulting emulsion droplet size distribution was measured using a particle sizer (Mastersizer Hydro 2000 SM, Malvern). Figure 2 shows the resulting droplet size distribution at three different ultrasound treatment times when using CIB and one blanc measurement with a non-treated bag. When comparing the CIBs with regular bags, the former showed a smaller droplet diameter than the latter; typically after one hour treatment the diameter is a factor of ten smaller. It can be seen that the CIB helps reducing the particle size over time, to a mean diameter of $d_{32} = 0.26 \mu m$. Compared to droplet mean diameters reported in literature [9], we find that the use of the CIB has resulted in a mean diameter that can be compared with classic emulsification techniques such as a high pressure homogeniser. The associated energy consumption based on the electrical power consumption (640W) is estimated to be on the order of $7 \cdot 10^3 \text{ J/m}^3$. 
Figure 2. (a) Droplet size distribution at 4, 10 and 60 minutes ultrasound treatment times inside the CIB, and after 60 minutes in an untreated bag (red dashed line). (b) Microscope image of the obtained emulsion after 60 minutes in the CIB.

4. Discussion & Conclusions

Using low- and high-speed imaging techniques, we showed that cavitation activity increases significantly inside the CIB. The liquid temperature inside the CIB reaches the bath temperature in less than 2 min, and the CIB wall material does not attenuate considerably the ultrasound transmission. Numerical simulations predicted an ultrasound attenuation of 0.7%, whereas experiments showed an attenuation of 7.7%; vibrations of the CIB may have led to a changed acoustic field and therefore a larger reduction in pressure. This difference in attenuation values is important as it refers to the loss in ultrasound pressure and bubble creation efficiency. From our simulations we found that the orientation of the bag does not cause such a large attenuation. The bubbles generated can perform surface modifications on different materials (cleaning indicator dye and removing 3D printed parts support materials with complex geometries). Sonochemical reactions can be performed inside the CIB, as illustrated by sonochemiluminescence imaging. We also presented promising preliminary results for using the CIB as emulsification device. We can conclude that the CIB is a versatile tool for performing acoustic cavitation studies, in which the cavitation is spatially controlled by the use of small pits inside the bag.

5. References

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