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2013

Yang, Y., Wang, Q., & Tan, S. K. (2013). The roles of acoustic cavitations in the ultrasonic cleansing of fouled micro-membranes. *Proceedings of Meetings on Acoustics*, 19.

<https://hdl.handle.net/10356/96772>

<https://doi.org/10.1121/1.4798756>

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Proceedings of Meetings on Acoustics

Volume 19, 2013

<http://acousticalsociety.org/>

ICA 2013 Montreal
Montreal, Canada
2 - 7 June 2013

Physical Acoustics

Session 1pPAa: Acoustics in Microfluidics and for Particle Separation IIb: Bubbles and Drops

1pPAa2. The roles of acoustic cavitations in the ultrasonic cleansing of fouled micro-membranes

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This paper described the experimental studies on the de-fouling mechanism of acoustic cavitation bubbles near the fouled micro-membranes. The presence of the membrane created asymmetry in the flow field, which forced the cavitation bubble to oscillate non-spherically and finally brought forth the jet impact directed to the membrane. The oscillations and micro-jets of the cavitation bubbles enhanced the nearfield dynamic features of the fluid and improved the performance of de-fouling. The acoustic multi-bubble system is complex. In this study, the authors first focused on the individual bubble dynamics near a solid boundary. A succession of individual cavitation bubbles were created by using Q-switched Nd: YAG laser pulses. The evolutions of the bubble dynamics were observed using a high-speed camera (up to 100,000 frames per second). The pressure impulses induced by the jet impact were detected by using the hydrophone system. The pressure impulse was quite intensive as compared with the hydrostatic pressure and was strong enough to dislodge the adherent fouling elements. The authors studied the cavitation bubble dynamics for different laser energies and stand-off distances from the boundary and tried to evaluate the influence of cavitations in the ultrasonic cleaning of micro-membranes.

Published by the Acoustical Society of America through the American Institute of Physics

1. INTRODUCTION

Cavitation bubble dynamics have been studied extensively for about a century (Rayleigh 1917). Traditional research activities on violent bubble dynamics have generally been associated with cavitation damages on ship propellers, fluid machinery and piping systems, as well as underwater explosions (Plesset & Prosperetti 1977; Philipp & Lauterborn 1998). Recently, researches on cavitation applications have taken on some new directions into ultrasonic cleaning (Chen, et al. 2006; Lauterborn & Urban 2008); sonochemistry (Dahnke, et al. 1999), and certain medical surgeries and practices (Klaseboer, et al. 2007; Calvisi, et al. 2008).

The study on the acoustic multi-bubble system in the ultrasonic cleaning was quite complicated (see FIGURE 1), so the authors focused on the individual bubble dynamics near a solid boundary firstly. There are two popular methods of generating a single cavitation bubble: spark generation (Kling & Hammitt 1972) and laser generation. The technique of laser-induced cavitation has become possible since 1970s (Lauterborn & Bolle 1975). This technique of bubble generation has certain advantages over spark generation (electrode influences flow field), and has gained popularity. In this method, an extremely short (6ns) and strong Q-switched laser pulse is focused into the water, and a single bubble will then be generated. A high-speed camera operated at up to 100,000 frames per second is typically employed to capture the bubble evolution during the whole life span of the bubble which lasts only for a short several hundred microseconds. The authors compared the cavitation bubble dynamics with different incident laser energies and stand-off distances from the solid boundary, and tried to deduce the main influence on the cleaning mechanism of acoustic cavitations.

FIGURE 1. Ultrasonic field induced by the ultrasonic processor for different acoustic intensities (VCX 500, SONICS & MATERIALS, INC.), the white vacancies in the field indicate the acoustic cavitations.

2. EXPERIMENTAL SETUP

An individual cavitation bubble was generated by using a focused laser pulse generated from a Q-switched Nd:YAG laser (LOTIS TII LS-2134UTF, wavelength 532 nm, pulse duration approximate 6 ns). The evolution of the cavitation bubble was observed using a high-speed camera system which was manufactured by Olympus (i-SPEED 3), with a record speed of 100,000 frames per second. The back lighting for the filming was generated using a high-power LED flashlight (WARSUN MX900, up to 900 lumen). A hydrophone system was employed to detect the shock wave signals induced by the cavitation bubble, which was acquired from Precision Acoustics (Needle Hydrophone system, 1.0 mm probe, 28 micron thick gold electroded Polyvinylidene fluoride (PVdF) film) and the output signals were recorded by using a digital oscilloscope (Tektronix DPO 2012) with a sampling rate of 1 billion samples per second (GS/s). The side walls of the cuvette (25 mm in length and width, and 75 mm in height) were made of microscope slides (SAIL BRAND), and a PVC plate was used as the rigid boundary. The cuvette was positioned on a micro-translation stage (STANDA), which had a traversing range of 15 mm, and a sensitivity of 0.01 mm.

FIGURE 2. A photograph of the experimental setup, including the bubble generation system, the high-speed observation station and the acoustic detection system.

3. EXPERIMENTAL RESULTS

A typical sequence of pictures of the first two oscillations of a bubble near a solid boundary captured using the high-speed camera (at 100,000 fps) is shown in FIGURE 3. The bubble has a maximum expanded radius $R_{max} = 1.5$ mm, and the stand-off distance is $ds = 3.0$ mm ($\gamma = ds/R_{max} = 2.0$). The first frame that recorded the bright flashing caused by the laser-induced plasma is accounted as the inception time of the bubble. The bubble is approximately spherical during the first cycle of oscillation. It can be seen that, a small elongation perpendicular to the boundary has developed during the late stage of the collapse (see frames 27 to 29). Shortly before the end of the first collapse, a jet is formed on the upper part of bubble, which subsequently penetrates the opposite (lower) bubble wall. After jet impact, the bubble becomes toroidal (the jet flow inside the bubble is not distinct), rebounds and gradually forms an inverse spade shape. A counterjet forms on the top of the bubble during the rebounding phase, but disappears during the ensuing collapse phase.

FIGURE 3. Evolution of bubble shapes for the case $R_{max} = 1.5$ mm and $\gamma = 2.0$ as captured using the high-speed camera set at 100,000 fps. The size of each frame is 4.6×6.2 mm.

When the bubble is generated closer to the rigid boundary, $\gamma = 1.0$, the bubble evolves in quite different patterns, see FIGURE 4. Before the jet impact, the bubble oscillates nearly spherically and the bottom of the bubble becomes a little flattened during the first collapse phase. After the jet impact, the bubble expands and collapses like a cookie on the solid boundary.

FIGURE 4. Evolution of bubble shapes for the case $R_{max} = 1.5$ mm and $\gamma = 1.0$ as captured using the high-speed camera set at 100,000 fps. The size of each frame is 4.6×6.2 mm.

After comparing the upper bubble evolutions, one can discern that the stand-off distance influences the bubble dynamics greatly for the same maximum bubble radius. FIGURE 5 present a series of pictures which show the transformations of bubbles created at different distances away from the solid wall for the same maximum bubble radius. In each row, the first frame shows the initial bubble shape for each case. The third frame of each sequence is the first maximum expansion phase of the bubble, and can be observed that the bubbles are of approximately equal radius in the equatorial plane, and $R_{max} = 1.4$ mm. The fifth frame is the first minimum phase just after or before jet impact. The sixth frame and those that follow show the next cycle which include both the expansion and collapse phase. For the cases $\gamma \geq 1.0$, the bubble shapes are similar before jet impact. One can clearly discern the different patterns after jet impact due to the influence of the solid bottom. As for the cases $\gamma < 1.0$, the bottom of the bubble will touch the solid bottom before jet impact. As such the pattern will be different even during the first cycle. The pictures captured in this study also confirm earlier suggestion that the counterjet only takes place for $\gamma > 1.0$ (Vogel, et al. 1989).

FIGURE 5. Comparison of bubble shapes captured at 100,000 fps for $R_{max} = 1.4$ mm with various stand-off distances: (a) $\gamma = 0.4$; (b) $\gamma = 0.8$; (c) $\gamma = 1.1$; (d) $\gamma = 1.4$; (e) $\gamma = 1.9$; (f) $\gamma = 2.2$. The size of each frame is 4.6×6.2 mm.

When a bubble and jet impact takes place, a pressure wave will be generated and the impulse so formed can be detected through acoustic means (Wolfrum, et al. 2003). A hydrophone system with a sampling rate of 1 billion samples per second (GS/s) will be able to capture these transient pressure impulses. One would then be able to estimate the intensity of the pressure impulses indirectly through the peak values of the impulses. FIGURE 6

shows the comparison of the acoustic signals for different stand-off distances with the same maximum bubble radius. One can find that the peak values of the pressure impulses at the jet impact time are nearly the same for these three cases, which are much larger than those for the hydrostatic pressure. This intensive shock wave pressure is the main force that dissociates the fouling on the micro-membranes.

FIGURE 6. Comparison of acoustic signals detected by the hydrophone system for $R_{max} = 1.4$ mm with different stand-off distances: $\gamma = 0.4$, $\gamma = 1.4$ and $\gamma = 2.2$.

4. DISCUSSIONS AND CONCLUSIONS

It can be observed that a cavitation bubble is formed when the incident laser pulse has provided sufficient energy to tear the liquid apart. The bubble will expand to a large size, and the maximum expanded size is a function of the laser energy imparted. The different magnitude between the interior gas pressure and the exterior liquid pressure causes the bubble to oscillate. When a bubble is generated near a solid boundary, the radial flow in the direction towards the boundary is retarded. The result is unequal pressure distribution across the bubble surface. This pressure gradient produces different accelerations of the upper and lower bubble wall, and leads to the formation of a jet on the upper wall of the bubble. After the jet has penetrated the opposite bubble wall, the bubble becomes toroidal. If the initial stand-off distance is greater than the maximum bubble radius, a counterjet will appear on the top of the toroidal bubble after the jet impact, and disappear gradually during the second collapse phase. However, if $\gamma < 1$, the jet impacts on the solid boundary directly and the counterjet will not be formed. The intensive pressure impulses induced by the acoustic cavitations are the important cleaning mechanism in the ultrasonic field.

ACKNOWLEDGMENTS

This work was supported by the School of Civil and Environmental Engineering, DHI-NTU centre, Nanyang Environmental and Water Research Institute and Maritime Research Centre of Nanyang Technological University.

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