Enhancing acoustic cavitation using artificial crevice bubbles

Aaldert Zijlstra^a, David Fernandez Rivas^{b,*}, Han J.G.E. Gardeniers^b, Michel Versluis^a, Detlef Lohse^a

^a Physics of Fluids Group, MESA + Institute for Nanotechnology, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands

^b Mesoscale Chemical Systems Group, MESA + Institute for Nanotechnology, University of Twente, 7500 AE Enschede, The Netherlands

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ABSTRACT

We study the response of pre-defined cavitation nuclei driven continuously in the kHz regime (80, 100 and 200 kHz). The nuclei consist of stabilized gaspockets in cylindrical pits of 30 μm diameter etched in silicon or glass substrates. It is found that above an acoustic pressure threshold the dynamics of the liquid–gas meniscus switches from a stable drum-like vibration to expansion and deformation, frequently resulting in detachment of microbubbles. Just above this threshold small bubbles are continuously and intermittently ejected. At elevated input powers bubble detachment becomes more frequent and cavitation bubble clouds are formed and remain in the vicinity of the pit bubble. Surprisingly, the resulting loss of gas does not lead to deactivation of the pit which can be explained by a rectified gas diffusion process.

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1. Introduction

Most applications based on acoustic cavitation, such as ultrasonic cleaners, emulsifiers or sonochemical reactors, rely on the spontaneous and seemingly random appearance of cavitation bubbles [1–3]. The subsequently generated cavitation state, meaning the bubble sizes, locations, dynamics and complex bubble–bubble interactions among others [4], are very difficult to describe and even more difficult to control [5]. This is mainly due to the inherent chaotic nature of cavitation and its complex dependence on the liquid and acoustic parameters. Manufacturers and researchers therefore have to resort to empirical methods to optimize the desired mechanical or chemical effects induced by acoustic cavitation bubbles [6–9]. The resultant of these effects is not only determined by the magnitude of the response of each individual bubble, but also by the total number of bubbles and their locations. The increase of cavitation activity would seem just a matter of increasing the acoustic amplitude, or input power. However, due to effects such as acoustic shielding and bubble–bubble interactions, this does not necessarily lead to an increase in efficiency [10–12]. There is also a frequency dependent lower acoustic power threshold for cavitation activity, usually referred to as the nucleation threshold [13]. Hence in the situations where lower acoustic amplitudes are required, e.g. to prevent heating or surface damage [14], it might not even be possible to generate or sustain a sufficiently active bubble population.

Enhancing cavitation mediated effects can be achieved by actively regulating not only the acoustic pressure amplitude, but also the bubble population. Therefore, an ideal solution is to introduce microbubbles of resonant size into the liquid. Various studies have shown that the presence of *ultrasound contrast agents* – microbubbles stabilized by an external shell – significantly enhances cavitation related effects [15,16]. Other methods such as bubble injection using gas flow through membranes [17], or flow focusing devices [18] could also be beneficial for increasing bubble populations in acoustic cavitation.

Here we present results of a different method to locally enhance acoustic cavitation activity in a continuous ultrasound pressure field. Our method consists of introducing microbubbles into the liquid which are entrapped and stabilized in micromachined and well defined cylindrical crevices, an image of which is shown in Fig. 1(b). These bubbles are essentially artificial versions of naturally occurring cavitation nuclei better known as “crevice bubbles” [19,20]. Bubble detachment from crevice bubbles occurs, not only in cavitation inception, but also in supersaturated liquids such as carbonated beverages [21,22] and in liquid pool boiling [23]. The use of artificial crevice bubbles was motivated by earlier studies of our group [24–27] where the response of the entrapped bubble to a single shock wave was investigated. Here we study the dynamics of stabilised cylindrical pit bubbles under continuous ultrasound irradiation. It will be shown that the presence of stabilised microbubbles significantly enhances local cavitation activity due to acoustically induced microbubble detachment from the pit bubble liquid–gas interface.

* Corresponding author.

E-mail address: d.fernandezrivas@utwente.nl (D. Fernandez Rivas).

A spherical bubble dissolves under ambient pressure and surface tension or rises to the surface due to buoyancy, while an entrapped bubble can be in a stable mechanical and diffusive equilibrium for an extended period of time. The presence of a crevice bubble nucleus basically constitutes a “weak-spot” in the liquid. Any change in the pressure or gas saturation conditions will cause a volumetric response of the bubble as it seeks to re-establish an equilibrium state. *Nucleation* is the event where the equilibrium cannot be established and the bubble expands out of the pit [20,27]. The three different but interrelated ways for this to occur are pressure reduction, increase in gas saturation or by a rise in temperature.

It is important to make a distinction between nucleation, i.e. the unstable growth of the bubble outside the pit, and a possible bubble detachment from the nucleus. Many authors use the term nucleation for the combined process, however the underlying mechanisms are different. Nucleation refers to the observable unstable growth of the liquid gas interface. Once nucleated, the bubble can become elongated and form a contracting neck until detachment takes place. This process which we refer to as *pinch-off* can occur due to buoyancy, liquid drag or acoustic pressure gradients. However, as will be shown, detachment of a bubble from the interface can also occur *without* bubble nucleation.

Bubble detachment following nucleation is a well studied effect in nucleate boiling [28] and particularly in supersaturated liquids [22] but surprisingly not in acoustic cavitation. Even though bubble detachment from entrapped surface bubbles is normally assumed to occur in acoustic cavitation, to our knowledge, there exist only a few studies in which this is actually reported. The first experiment reported consisted in holes of 200 μm diameter drilled in a sonotrode tip, in order to enhance cavitation effects at reduced acoustic amplitudes [29]. The growth of bubbles, surface instabilities and bubbles leaving the holes were observed. Erosion studies on brass surfaces from bubbles nucleated from a bubble stabilised on a pit of 1 mm diameter and depth, drilled on the sonotrode surface at 20 kHz, have also been reported. In degassed water and in the absence of the drilled pit, erosion effects were not observed [30].

Here we are interested in the response of artificial pit bubbles to a continuous acoustic field, and how its response can contribute to the enhancement of cavitation activity. In the following, the process of bubble nucleation and detachment by pinch-off in acoustic cavitation is investigated in more detail using high-speed imaging methods.

2. Materials and methods

2.1. Machining of pits

In order to obtain pit bubbles which are comparable in size with naturally occurring crevice bubbles, but large enough to allow

visual observations, we chose to create cylindrical pits of 30 μm in diameter. The pits with depths of $\sim 10 \mu\text{m}$ and 6 μm were etched both in polished silicon wafers as well as in fused silica glass, see Refs. [10,12] for more details. We found by optical inspection that a stable liquid–gas micromeniscus was always present after immersion of the substrate even though no extra measures were taken to increase the hydrophobicity of the pit as was done in the past [24,25].

2.2. The acoustic field

In this study, three setups were used. The silicon substrates were placed on the bottom of one of two small containers providing stability, liquid containment and convenient optical access. The first type of container was a cubic cuvette (Hellma Analytics), made of optical quality quartz glass with inner dimensions $1 \times 1 \times 1 \text{ cm}$. The second type was cylindrical with an inner diameter of 1.5 cm and a depth of 3 mm. The acoustic field was generated by means of a piezoelectric element (Ferroperm PZ27, 6 mm thickness and diameter of 2.5 cm) glued to the containers (see Fig. 1). The maximum response of the piezo and cuvette combination when filled with water was found to occur at frequencies close to 80 kHz and 200 kHz corresponding to radial and thickness vibration modes.

In order to take full advantage of the transparency of the glass substrates with pits, a system described in the literature was used [31]. Here, the glass substrates together with four piezo elements were glued to a glass microscope slide. Upon adding demineralized water (left standing for one day to ensure full saturation) onto the substrates, a pocket of air was entrapped within the cylindrical pits. The presence of the liquid–gas interface was verified using dark-field illumination microscopy.

The piezoelectric elements of the cuvette systems were actuated using a continuous sinusoidal voltage generated by a function generator (model WW1072, Tabor Electronics Ltd.) which was amplified using a wide band amplifier (Krohn-Hite, model 7602). The glass system was actuated by an arbitrary wave generator Agilent 33522A and amplified with an AG series amplifier T&C Power Conversion. The input voltage and current signal were measured using an oscilloscope (Tektronix, DPO 4043) and a current probe (Tektronix, CTA-2). The small liquid volume and the close proximity to the piezo element complicated the pressure measurements, therefore the input electrical power was taken as a relative measure of power. The acoustic power cannot be directly quantified for these values.

The applied acoustic field is continuous, therefore a standing wave is formed in the container depending on the shape and dimensions of the liquid volume. It was found that the largest response of the pit bubble occurred for liquid heights equal to

Fig. 1. Schematic of the piezo-cuvette combination (a) and pit (b) in side view. The diameter of the circular piezo is 2.5 cm and the side of the cuvette is 1 cm. (c) SEM image of a micromachined cylindrical cavity of 30 μm (2a) diameter and 10 μm depth (h) in a silicon substrate. Photograph (d) of a square silicon substrate of 1 cm side held by a tweezer, and piezo glued to the quartz glass cuvette.

Fig. 4. Sequence of frames from a 500 kfps high-speed movie showing the response of the pit bubble during 2.5 acoustic cycles. In the second cycle from 12 to 24 μ s a 5 μ m diameter microbubble is pinched off.

R2009b[®]. Due to motion blur in the high speed videos only the trajectories of bubbles emerging some 100 μ m above the pit could be resolved. Two obtained time traces are shown in Fig. 5, one for the irregular type pinch-off (a) and one for the regular type pinch-off (b). It reveals that the bubble pinch-off processes are quite erratic, both in pinch-off rate, as well as the ejected bubble sizes. At some instances (e.g. near 60 ms in Fig. 5(a)) bursts of multiple bubbles with radii less than 5 μ m are expelled, but it can take several milliseconds before the next pinch-off event. The average rate of bubble pinch-off for these traces was 2 kHz or every 40 acoustic cycles. The bubble size distributions shown in the insets in (a) and (b) show that the majority of the ejected bubbles had radii less than 7 μ m, whereas the larger bubbles form during bubble coalescence. The irregular type pinch-off process results in bubbles with radii near 2 μ m with a broader size distribution. Bubble coalescence was more prevalent in the first type, forming larger bubbles compared to that of the second type as reflected in the bubble distributions. Bubbles smaller than μ m in radius were observed but a precise quantitative determination of their radius was not possible due to limited image resolution.

For the regular type of pinch-off it was found that the velocity of the bubbles immediately after pinch-off was typically as high as 2 m/s and slowing down to about 50 mm/s at 200 μ m above the substrate. For the irregular type pinch-off the velocities were found to be an order of magnitude lower. The larger number of bubble coalescence events observed in this regime compared to the regular type can be related to these lower velocities.

3.1.2. Driving at 200 kHz

Here the cuvette setup is used again but now imaged in top view with the Brandaris 128 high-speed camera. The driving frequency is approximately twice the linear resonance frequency (98 kHz) of the pit and lies below the first higher harmonic of 243 kHz [36]. Similar to previous observations, there is a threshold for the pressure above which bubble pinch-off occurs corresponding to an input power of 50 mW. Interestingly, in the regime below this threshold the liquid–gas interface exhibits alternating dark and bright rings which appear to move radially outward periodically with the driving frequency (see Fig. 6(a)).

A sequence of frames taken from a high-speed movie is shown in Fig. 6(b) with driving pressure slightly above the threshold

Fig. 5. Ejected bubble events marked by bubble radius in time for the irregular type pinch-off (a) and regular type pinch-off (b). The insets show the histograms with N_b the number of bubbles. The data was obtained from 15 kfps high-speed movie recordings. The image resolution did not allow bubble sizing for radii smaller than 1.3 μ m (indicated by the gray areas in the distributions).

(50 mW). Here the rings are no longer visible and occasionally bubbles are pinched off which in turn respond to the acoustic field by expansion and collapse. In this regime the bubbles that are pinched-off generally are drawn back into the pit bubble within at most 3 acoustic cycles due to mutual acoustic forces. In contrast to the 80 kHz driven pit bubble, the ejected microbubbles do not move upward but remain in close proximity of the substrate. From

many similar recordings in this regime it was observed that once a bubble is detached from the pit bubble, a subsequent pinch-off event will not occur as long as the bubble is not recaptured. As shown in Fig. 6(c), increasing the input power enhances the deformation of the interface and bubbles are continuously pinched-off from the liquid gas interface. Also the number of free bubbles oscillating just outside the pit perimeter increases as well as their

Fig. 6. Four sequences of frames taken from high-speed recordings in reflective imaging mode (top-view) of the pit for increasing driving input power. Sequence (a) is at approximately 45 mW showing ring-structures. Increasing the driving power to 50 mW induces interface deformation and pinch-off (b). Further increase (79 mW in (c) and 235 mW in (d)) both increases the bubble number and maximum expansion. Note the different scale in (d). [Supplementary Video](#).

maximum expansion size. The bubbles still remain close to the pit bubble and are observed to oscillate up to 3 or 4 cycles before breaking-up or coalescing with the pit bubble or other bubbles.

The same trend is observed for larger driving input powers; more bubbles are pinched-off expanding to larger volumes with dimensions exceeding the diameter of the pit. As illustrated in Fig. 6(d) a cavitation bubble cloud is formed which is centered on the pit. Here both bubble deformation, coalescence and break-up are more pronounced compared to lower driving conditions (Fig. 6(b) and (c)). Due to these effects, the bubble population changes with every acoustic cycle. The response of an individual bubble in the cloud can therefore only be distinguished and followed in time during part of the expansion phase of the cycle (e.g. from 0.7 μ s to 3.3 μ s).

The increase in the number of bubbles with increasing driving input power is shown in the graph of Fig. 7. The estimates for the number of bubbles were obtained from high-speed recordings at different input powers. The number of bubbles varies considerably with each acoustic cycle (e.g. compare Fig. 6(d) at $t = 0.7 \mu$ s and $t = 6.5 \mu$ s) resulting in a large variance. Exact bubble counts were difficult to obtain due to the limited resolution of the optical system and due to the image processing detection limit when the pinched off bubbles were located close to the pit bubble or in contact with other bubbles.

The growth of the bubble cloud with increasing power is illustrated in Fig. 8. The frames in (a) show the scattered light from the bubbles in dark-field illumination mode giving an indication of the extent of the cloud. The corresponding frames in (b) obtained using iLIF imaging reveal the individual bubbles. From similar images the size of the bubble cloud was measured (Fig. 8(c)). Similar to what was observed at 80 kHz, the pit is not deactivated by loss of gas due to pinch-off processes. It was found that the cavitation cloud can remain stable for at least an hour, only to disappear when the acoustic field became disrupted due to evaporation of the liquid from the cuvette.

3.2. Glass microscope slide

The setup with the glass substrates enabled a better top-view imaging of the dynamics of the liquid–gas interface in the pit than the silicon substrates. A typical image sequence of the response of the interface to an 99.5 kHz standing acoustic field obtained with this setup with voltage amplitude value 400 mV is shown in Fig. 9. Further details on the characteristics and operation of this setup are reported in the literature [31,37].

Fig. 7. Average number of bubbles during one acoustic cycle for different input powers at 200 kHz.

3.2.1. Driving at 99.5 kHz, glass substrates

Following the initiation of the acoustic field at $t = 0$ the interface sequentially expands outward and back inward in a drum membrane-like fashion corresponding to the visual changes in brightness (first row). The oscillatory motion was occasionally interrupted as in the 5th frame. Here, during the inward motion the center of the interface comes into contact with the bottom of the pit which is shallower than those used in the silicon substrates. It appears that due to this contact the now toroidal interface becomes destabilized and detaches from the top right rim of the pit ($t = 33.3 \mu$ s). In the following cycles the contact line of the gas volume retracts further until a circular shape is attained ($t = 266.7 \mu$ s). Coinciding with this deformation a continuous stream of small bubbles is ejected from the bubble interface along the new axis of symmetry formed by the pit and the bubble (indicated by the white arrow at $t = 277.8 \mu$ s). The bubbles are estimated to have diameters between 1 and 2 μ m and are ejected once every two acoustic cycles. A clear pinch-off event could not be distinguished from these recordings, however similar to Fig. 4, the detached bubbles emerge during the contraction phase of the liquid–gas interface.

Once the bubble attains its spherical shape it remains attached for an extended period of time to the lower left corner of the pit while oscillating with a maximum diameter (in lateral dimensions) of 20 μ m (see e.g. $t = 288.9 \mu$ s). During the contraction phase, the bubble adapted an oval or bean-like shape. Occasionally, the bubble contraction occurred faster than the translation of the liquid–gas contact line over the substrate resulting in semicircular bubble extensions (see e.g. $t = 272.2 \mu$ s or $t = 2494 \mu$ s). At times, this lagging of the interface even resulted in a dual pinch-off from the edges of the bubble ($t = 2506 \mu$ s). Another phenomena occurred when larger bubbles were formed either by pinch-off or coalescence ($t = 9911 \mu$ s). These bubbles remained in proximity of the larger bubble, presumably due to secondary Bjerkness forces.

3.3. Interaction of cavitation clouds and surface damage

In Section 3.1.2 it was shown that in the presence of a single pit bubble, cavitation activity is initiated and sustained which would not occur without a pit under similar conditions. A natural solution to augment this activity is to introduce additional pits.

Indeed, as shown in the images in Fig. 10 another cavitation bubble cloud is generated from a second pit. Here the two pits (30 μ m diameter) are 1000 μ m apart. At low driving power the individual clouds appear similar to the single pit system described in the previous section. At elevated powers (648 mW) the center of mass of the clouds is translated towards the neighboring pit through mutual attraction (Fig. 10(iv)). Increasing the power further, the clouds merge at the midpoint (Fig. 10(v) and (vi)). The transition between the two states occurs just above 648 mW driving power (iii) and is quite abrupt, meaning that the intermediate states between (iv) and (v) are unstable and very sensitive to pressure [4]. At higher power the cloud broadens, similar to the case of a single pit. Likewise, further increase in power does not produce a noticeable expansion of the cavitation cloud. The merging of the clouds results in a peculiar ribbon-like structure with a wider section in the middle measuring $\sim 200 \mu$ m in diameter.

In order to illustrate the dynamics of the bubbles in the clouds a sequence of frames from a high-speed recording (Brandaris, 1.48 Mfps Supplementary Video) is shown in Fig. 11. The pits are located in the lower-right and upper-left corners. The first frame shows the bubble cloud with the bubbles at maximum expansion (similar to the frames (v) and (vi) in Fig. 10(b)). During the following cycles (5 μ s duration) the majority of the bubbles in the cloud collapse and expand again in phase. A few considerably larger bubbles can be observed which, due to their size, exhibit a phase

Fig. 8. (a) Six frames from the 30 μm diameter pit bubble response for increasing input power obtained with dark field illumination at 200 kHz. (b) The corresponding response for the single pit bubble and its induced cavitation cloud obtained with ultrashort flash photography. (c) Graph of the diameter of the cloud for increasing driving power. The frames (i)–(vi) in (a) and (b) are indicated in the graph.

difference with respect to the response of the other bubbles. For example the large bubble close to the lower-right corner continues its collapse until about 4 μs (7th frame) while the other bubbles have already started expansion. Similar to the single pit bubble cloud, the bubbles display coalescence, break-up and deformation, in particular the larger bubbles, due to the proximity to the substrate (attractive secondary Bjerknes forces as described elsewhere [4]). It is therefore difficult to track individual bubbles in these images. However the recordings do reveal that, on average, bubbles translate after pinch-off from both pits towards the center of the cloud. In this region a mist of small microbubbles can be observed during the high pressure phase of the acoustic cycle (e.g. at 2 μs and 12.2 μs).

These small bubbles can result from increased bubble fragmentation taking place in this region combined with dissolution. Also in this case, the remarkable stability of the cloud, which was studied for at least one hour, suggests that the process is strongly dependent on diffusive transport of dissolved gas. In addition, the recordings shown in Figs. 8 and 10 demonstrate the resilience of the pit bubbles to dissolve. Evidently, even the strong pressure fluctuations associated with multiple bubble expansions and collapses are insufficient to destabilize the crevice bubble. A more detailed study of these type of bubble phenomena relevant for sonochemical activation is given elsewhere [11].

After several hours of US exposure a pattern of surface damage appeared on the substrate, which was consistent with the region of cavitation activity. The shock waves originating from the collapse of bubble clusters are also associated with the generation of surface damage. Further details on the damage of different crystallographic silicon substrates and practical uses for cleaning that these type of cavitation conditions can provide are given elsewhere [38,39].

4. Discussion

Jetting has been defined in certain cavitation experiments as the inertia-driven passage of liquid flow through a gas bubble in the proximity of another bubble, or a wall. These bubbles collapse asymmetrically which can lead to physical changes in nearby cells, cleaning of substrates and erosion of surfaces [38–40]. A specific type of capillary break-up is also termed “jetting”, but in this case refers to the ejection of small bubbles as a result of flow focusing of a gas in a liquid [18,41,42].

For the experiments at 80 kHz (Section 3.1.1) we could capture this second type of jetting, where the gas–liquid interface was perturbed by the strong oscillations driven by the piezo actuation. From the observations at all frequencies we speculate that the bubble pinch-off occur by a “folding” of the liquid–gas interface resulting from large amplitude capillary waves. These closed capillary waves resemble what is known as “Crapper wave” solutions [43]. The regime shown in Fig. 3(a) where bubbles are pinched-off from different locations on the interface then correspond to a shorter capillary wavelengths compared to the regime shown in Figs. 3(b) and 4. Another explanation is that the liquid–gas interface becomes deformed in such a way that the cylindrical symmetry of the pit bubble is broken, and the character and locations of pinch-off changes, as will be further discussed (see Fig. 9).

For the particular case of pinch-off at 80 kHz driving (Section 3.1.1), all of the observed ejected bubbles, have radii much smaller than the linear resonance radius of 38 μm [1], as expected. In comparison, the resonance frequencies for the first and second surface mode for this pit are 139 kHz and 276 kHz respectively, based on linear potential flow analysis [36]. This explains the larger amplitude response of the pit bubble compared to that of the ejected

Fig. 9. Series of frames taken from a high-speed recording (Photron, 180 kfps, 1 μs exposure time) of the glass pit at 99 kHz and voltage amplitude of 400 mV. The first oscillations occur as a drum membrane until $t = 27.8 \mu\text{s}$. The bubble detaches from the rim of the pit and attains a shape close to spherical and stabilizes at one corner of the pit. Subsequent oscillations produce interface deformation and microbubble pinch-off from more than one location on the bubble surface. The white arrow at $t = 277.8 \mu\text{s}$ indicates a continuous stream of small bubbles ejected from the bubble interface along the new axis of symmetry formed by the pit and the bubble.

bubbles. For example, from the Rayleigh–Plesset equation [1] it follows that a spherical bubble with an equilibrium radius of 3 μm would expand to a maximum radius of 4 μm for an acoustic pressure amplitude of 90 kPa at 80 kHz. Such (ejected) bubble expansions were not observed, therefore it follows that the local

pressure value within the field of view must have been smaller than 90 kPa.

For the case of 99.5 kHz (Section 3.2.1), a similar situation occurs as at 80 kHz. The stabilised and close-to-spherical bubble continuously emits smaller bubbles, but its size does not decrease

Fig. 10. The development of the bubble cloud originating from two pits of 30 μm diameter, 1000 μm apart. The 6 rows correspond to 6 steps of increasing acoustic input power. The left column illustrates the time averaged extent of the cavitation cloud. In the right column the individual bubbles can be distinguished, here taken at approximately maximum expansion.

nor does it dissolve all together. In this case the (horizontal) stream of bubbles ceased when the bubble detached from the lower left corner of the pit and relocated to the center of the pit ($t = 47228 \mu\text{s}$). Interestingly the bubble started to oscillate, alternating from spherical to ring or donut shaped (last row of Fig. 9).

Based on the observations made in the glass substrate (Section 3.1.2) we attribute the rings that appear on the interface to surface mode oscillations. From these images it can be inferred that the interface retains its axial symmetry and oscillates at the same frequency as the driving acoustic field. This symmetry is lost however when the bubble oscillations amplitude increase.

Remarkably, the pit bubble constantly ejected microbubbles while the loss of gas did not result in diminishing or deactivation of the process in all studied frequencies. The pinch-off rate corresponds to a gas volume flux in the order of $100 \mu\text{m}^3/\text{s}$ away from the pit, which must be balanced by an influx of equal magnitude. This transport must be of diffusive nature, where a rectifying

mechanism can take place, similar to the well known process of rectified diffusion of spherical bubbles [44]. During oscillation of the meniscus, the gas pressure inside the pit bubble will rise during compression, and fall during expansion, respectively leading to gas diffusing out and into the pit bubble. Both the area effect and the shell effect may occur: the surface area of the meniscus is larger during expansion than during contraction, resulting in a net flow of gas into the pit bubble; the shell effect adds to this trend as the bubble expansion causes an increase of the dissolved gas concentration in the liquid adjacent to the meniscus while the opposite occurs during its contraction.

It is possible that the oscillation-induced microstreaming [45], draws in liquid from the bulk where the concentration of dissolved air is larger, thereby sustaining the pinch-off process. This same microstreaming can also account for the observed bubble trajectories, possibly in combination with primary and secondary Bjerkness forces [4].

Fig. 11. Frames from a high-speed recording of the dual pit cavitation cloud at 810 mW input power and imaged at 1.4 Mfps. [Supplementary Video](#).

5. Conclusion

We have demonstrated that the introduction of artificially created crevice bubbles into an acoustically insonified liquid results in a myriad of acoustic cavitation related phenomena. Streams of microbubbles are ejected into the liquid while for larger input powers cavitation bubble clouds are formed. The stability of both the pit bubble and the cavitation bubble clouds is enabled by diffusion of gas back into the pit bubble. The results of the exploratory study described here confirms the common assumption that cavitation activity can be initiated and enhanced by the presence of crevice bubbles. However, the mechanism with which bubble release transpires is different from bubble detachment occurring in e.g. nucleate boiling and supersaturated liquids. In these heat and gas diffusion driven processes, the bubble displays unstable growth outside the perimeter of the pit after which it detaches due to buoyancy or drag forces. The inception of a cavitation bubble due to detachment from a pit bubble does not appear to involve such nucleation and subsequent detachment. Here, the released bubbles are typically smaller than the pit bubble and may result from large amplitude capillary waves which locally “fold” the liquid–gas interface into a singularities.

In this study three different frequencies were applied, each displaying distinct types of bubble generation and cavitation activity. For future studies a larger parameter space should be explored with additional focus on the effect of amplitude, pit dimensions and gas content in the liquid.

Clearly, the use of artificial crevice bubbles constitutes a new method (with advantages over conventional US horns or baths) to initiate and enhance cavitation at any desired location, provided the liquid and acoustic parameters are appropriate. The unique control over cavitation activity enables detailed investigation of acoustic cavitation and its effects such as shock wave emission, damage formation or sonochemistry, as was demonstrated in previous studies [10–12,39].

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.ultras.2014.10.002>.

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