

Article

Vibrational Rarefaction Waves Excited by Laser-Induced Bubble within Confined Cuvettes and Their Feedback on Cavitation Dynamics: Influence of Wall and Liquid

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Abstract: In this work, within finite liquid spaces confined by elastic walls and the free surface, we investigated the influence of wall and liquid on laser bubble-excited vibrational rarefaction waves, via the dynamics of the laser-induced plasma-mediated bubble and its accompanying small secondary bubble clouds. We observed the modulation of the rebound maximum radius ($R_{\max 2}$) relative to the first oscillation period ($T_{\text{osc}1}$) for the laser bubble and the periodic appearance of secondary bubble clouds, which were caused by extra rarefaction waves. We found an approximate constant modulation period of $R_{\max 2}$ ($T_{\text{osc}1}$) and increased time intervals between the adjacent secondary bubble clouds with increasing liquid height in the same cuvette, while both of them were remarkably increased with increasing inner size of cuvettes within the same liquid height. This indicated that the cuvette geometry and liquid volume alter the key characteristics of the vibrational rarefaction waves. It was further confirmed that extra rarefaction waves within the liquid are excited by wall vibrations linked to laser bubble expansion and its induced liquid-mass oscillations. Our study provides a better understanding of the interactions of laser-induced cavitation with liquid and elastic walls in confined geometry, which is essential for intraluminal laser surgery.

Keywords: laser-induced bubble; vibrational rarefaction wave; secondary bubble clouds; elastic wall vibration; partial confinement



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1. Introduction

Laser-induced plasma-mediated bubble (laser bubble) holds significant importance in the field of cell surgery [1], laser lithotripsy [2,3], laser angioplasty [4,5], and nanostructure production [6,7]. It also presents promising prospects in applications such as the ablation of cardiovascular thrombus [8–10]. In these scenarios where the liquid is typically confined within elastic biological tubes such as ureters and veins as well as constrained by the tip of optical fibers, the interplay between laser bubbles and these elastic confined environments can profoundly influence the dynamics of the bubbles.

An increase in the ambient pressure within a liquid medium can cause a notable reduction in both the size and lifetime of bubbles [11–13]. In a finite liquid volume with strong confinement, bubble expansion is accompanied by a corresponding decrease in the liquid's volume, producing a substantial elevation of pressure within the liquid [14]. This elevated pressure, in turn, exerts a significant feedback effect on the bubble, leading to markedly compressed dynamics. Normally, a strong confined environment is achieved by introducing containers or tubes with limited-sized solid or elastic walls. The pressure rise during bubble oscillations also has strong feedback on the boundaries. Combined

with shock wave impaction, this may lead to wall deformation or container rupture when extreme excitation energies are used [15,16]. The strongest confinement effect occurs in a fully confined space with rigid walls, which increases with increasing bubble size and decreasing liquid volume. In contrast, when walls are elastic, the confinement effect is reduced due to their elastic response to bubble oscillations but still leads to significant compression of bubble dynamics. Studies by Fourest et al. [17] and Deletombe et al. [18], investigated the compressed bubble dynamics in a sealed tank induced by projectile penetration. Vincent et al. [19] demonstrated faster bubble dynamics than in free liquid when the negative pressure-driven bubble was induced in a fully confined space with elastic material by evaporation from the gel. In the meantime, theoretical models have been developed to describe the compressed bubble dynamics in a fully confined space by coupling the confined effect into the Rayleigh–Plesset or Keller–Miksis models [15,17,19–22].

Moreover, when the bubble is formed in the confining container with elastic thin walls, there have been indications of additional tensile pressures possibly ensuing from this interaction [14,23], giving rise to a pronounced secondary cavitation phenomenon [24,25]. Our previous work also showed that pressure rises originating from both bubble expansion and the consequent liquid-mass oscillations can induce wall vibrations [23,25]. These vibrations produce a sequence of alternating rarefaction waves characterized by potent tensile components with notable initiation time delay. Their feedback on the bubble results in a prolongation of the collapse phase, modulation to the second oscillation process, and time-delayed re-oscillations, as well as the formation of robust secondary cavitation in the liquid along the laser path [23,25]. Such mutated bubble dynamics depend not only on the energy input from the laser but also on the intrinsic characteristics of the pressure waves such as the onset time, eigenperiod, and the time intervals between adjacent rarefaction waves. By modulating key parameters of these waves, controllable laser-induced cavitation dynamics can be achieved, which presents a potential avenue to realize the improvement of desired therapeutic effects while minimizing undesired side effects during medical procedures. These vibrational rarefaction wave series should be closely linked to characters of liquid-filled cuvettes such as the geometry of the wall and liquid, but the specific details are still unclear and worth deeper investigations.

In this work, by monitoring laser-induced cavitation dynamics within partially confined cuvettes with varied cuvette inner sizes and liquid height, we investigated the influence of wall and liquid on the vibrational rarefaction waves. High-speed photography with a vast view in the horizontal direction and acoustic measurements were simultaneously used to measure the cavitation dynamics. The results revealed that, when increasing the liquid height within the same cuvette, the modulation period of $R_{\max 2}$ (T_{osc1}) was barely changed for the laser bubble, while both the inception time and the peak-to-peak interval of adjacent generations were increased for secondary bubble clouds. Conversely, all three parameters were increased on increasing the inner size of the cuvette with the same liquid height. This observation underscores the role of the elastic wall in determining the eigenperiod of the vibrational rarefaction waves, while the liquid properties dictate the onset time and time interval between adjacent waves. It further reaffirms that the rarefaction wave series originates from wall vibrations intricately linked to bubble expansion and its excited liquid-mass oscillations.

2. Methods

The experimental setup is illustrated in Figure 1. A Q-switched Nd: YAG laser (Quantel, Villejust, France, Q-smart 450) with a maximum repetition rate of 10 Hz and a pulse duration of 6 ns operated at a frequency-doubled wavelength of 532 nm was used to induce cavitation. The laser beam was focused within water using an achromatic doublet ($f = 15$ mm) in combination with a meniscus lens ($f = 100$ mm). A high-speed camera (Revealer, Hefei, China, X213) capable of recording at framing rates of 250,000 frames per second was used to record the cavitation bubble dynamics. For illumination, a xenon lamp (Beijing Princess, Beijing, China, PL-X500D) was utilized. A flat piezoelectric transducer

(Olympus, Tokyo, Japan, V324-N-SU) with a diameter of 9.25 mm (with 14–32 MHz bandwidth) was placed on the liquid surface for far-field detection of the acoustic transients produced during cavitation in conjunction with a digital oscilloscope (Rohde & Schwarz, Munich, German, PTE1204, which has a maximum bandwidth of 2 GHz and a maximum sampling rate of 5 GS/s). This transducer also served as a piston, confining the liquid. The timing coordination among the pulsed laser, oscilloscope, and camera was controlled by a delay generator (SRS Inc., Fremont, CA, USA, DG645).

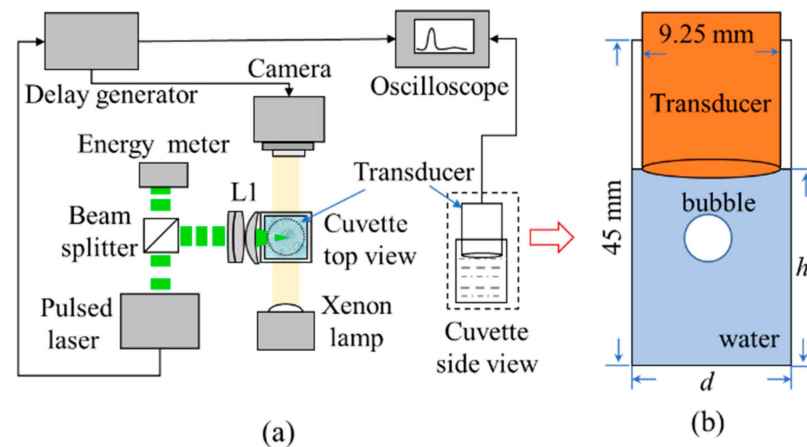


Figure 1. (a) Experimental arrangement for simultaneous high-speed photography and acoustic measurement of laser-induced cavitation dynamics in a confined cuvette; (b) Dimensions of cuvette and transducer, liquid height, and location of bubble. Here, d is the cuvette inner size, and h is the liquid height.

The liquid configuration within the glass cuvette is illustrated in Figure 1b. Cuvettes have dimensions of 45 mm in height, 1.2 mm in wall thickness, and ranging from 10 mm to 12 mm in inner sizes. Optical breakdown was excited in the center of the cuvette, and 9 mm beneath the transducer. During the experiments, three different heights of liquid, 27 mm, 32 mm, and 37 mm were used. To reduce the shock wave reflections from the cuvette bottom, a monolayer of glass spheres with a 1 mm diameter was put on the bottom of the cuvette. This work used deionized water with a resistivity of 18.2 M Ω , and all the experiments were performed at ambient pressure (1 Bar) and room temperature (20 °C).

3. Results and Discussion

Figure 2 presents the bubbles dynamics for the specific case $d = 10$ mm and $h = 27$ mm. An 827- μ J laser pulse was used, generating a laser bubble with $R_{\max}$ of 521 μ m and T_{osc1} of 122.6 μ s. An image sequence of a single breakdown event is shown in Figure 2a, and the temporal evolution of the laser bubble radius is depicted in Figure 2b. The laser bubble exhibits a considerably prolonged collapse phase compared to its expansion phase during the first oscillation, multiple re-oscillations during the after-bounces, and accompanied by the appearance of secondary bubble clouds along the laser path. This coincides with our previous studies in [23,25], which can be attributed to the extra vibrational rarefaction wave formation within the liquid.

It was observed that the laser bubble split into two parts after the first collapse in Figure 2a, which was associated with enhanced deviations from spherical symmetry during the late collapse phase by the interactions between the laser bubble and secondary bubbles [25] and by the elongated breakdown plasma formation [26,27]. The split of the laser bubble is not inevitable, and when this occurred, only the largest one was traced in calculating the temporal evolution of the laser bubble radius, as shown in Figure 2b. Compared to the dynamics of a bubble with the same $R_{\max}$ in free liquid (which was simulated by the Rayleigh–Plesset model [23]), the laser bubble shows a faster expansion phase and a

significantly prolonged collapse phase. The former is caused by the confined effect-induced pressure rise, and the latter is associated with the vibrational rarefaction wave.

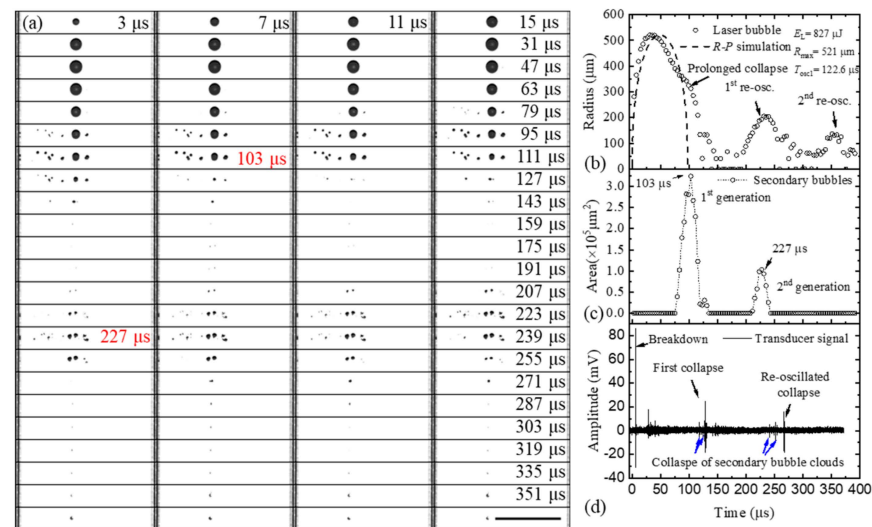


Figure 2. Cavitation dynamics for the case $d = 10$ mm and $h = 27$ mm. (a) Photographic series with a frame interval of 4 μ s. The length scale was 5 mm, with the laser pulse incident from the left; temporal evolution of the laser bubble radius and its comparison to the Rayleigh–Plesset simulation (b) and the total area of secondary bubble clouds on the upstream side of the laser bubble (c), determined from images series; (d) far-field acoustic signal. Shock waves emitted at secondary bubble collapse were detected (blue arrows).

Owing to the strong plasma shielding effect of ns pulse-induced breakdown [26,28–30], secondary cavitation on the downstream side of the laser bubble is very weak and occasional. In addition, with increasing pulse energy and laser bubble size, the secondary bubbles with increased density will inevitably coalesce with each other, which made it hard for us to track the temporal evolution of each secondary bubble’s size. Hence, we only calculated the total area of secondary bubbles in a fixed region on the upstream side of the laser bubble, and its time-dependent evolution is shown in Figure 2c. In this case, it reaches a first peak at 103 μ s and a second peak at 227 μ s.

Figure 2d depicts the far-field acoustic signal. Normally, the shock waves emitted at optical breakdown and bubble collapse are monopolar. Here, the strong negative part of measuring shock wave signals is an artifact. A suitable PVDF detector can be used for better detection of shock wave detection [31,32]. The breakdown shock wave was detected around 6 μ s after the optical breakdown. Considering the sound velocity of ~ 1500 m/s in water at ambient pressure and room temperature, this coincides with the vertical distance of 9 mm between the transducer and the optical breakdown location. In comparison to findings from other laser-induced cavitation studies, which were driven by negative rarefaction waves reflected from the free surface [33–38], bubble wall [39], or elastic boundaries [40–42], secondary bubble clouds generated by vibrational rarefaction waves exhibited larger sizes and longer lifetimes. The collapse of these large-sized secondary bubbles even produced detectable shock waves within the liquid in this work. Consequently, apart from the shock wave signals emitted at the first and re-oscillated collapses of the laser bubble, several other shock wave signals, albeit with reduced strength (blue and red arrows), were observed in their proximity, as shown in Figure 2d. For a spherical bubble in free liquid, the first collapse shock wave has a similar or even larger amplitude than the breakdown shock wave [27,43]. However, in this case, the strength of the first collapse shock wave was notably diminished compared to the strength of the breakdown shock wave, resembling the shock wave emitted at the collapse of the re-oscillating bubble with a considerably smaller size, as shown in Figure 2d. This can be attributed to the enhanced non-spherical

collapse, resulting from the asymmetrical interactions between the laser bubble and the secondary bubble clouds, as well as the direct influence of vibrational rarefaction waves.

Figure 3 depicts the evolution of $T_{\text{osc1}}/T_{\text{Ray}}$ with R_{max} . Here, T_{Ray} and R_{Ray} denote the first oscillation time and maximum size of the laser bubble in free liquid, respectively. Their linear relationship can be described by the Rayleigh formula $R_{\text{Ray}} = \frac{T_{\text{Ray}}}{1.83} \sqrt{\frac{p_{\infty} - p_v}{\rho}}$ [44]. The parameters are p_v the saturated vapor pressure, p_{∞} the static pressure, and ρ the liquid density. In this work, $p_v = 2330$ Pa, $p_{\infty} = 100$ kPa, and $\rho = 998$ kg/m³. T_{Ray} was calculated from R_{max} . The maximum radius of the laser bubble was reduced remarkably by the confined effect, leading to an underestimation of T_{Ray} . It was observed that the ratio $T_{\text{osc1}}/T_{\text{Ray}}$ slightly decreased with increasing bubble size at first, and reached a minimum at $R_{\text{max}} \approx 380$ μm , which corresponds to T_{osc1} of 65 μs . This is because, these laser bubbles collapsed before tensile vibrational pressure and only suffered from the confined effect-induced compressive pressure. On further increasing R_{max} and T_{osc1} , the laser bubble suffers from the strong tensile pressure of the vibrational rarefaction wave, leading to a rapid increase in the ratio $T_{\text{osc1}}/T_{\text{Ray}}$. It is worth noting that the growth rate of the ratio $T_{\text{osc1}}/T_{\text{Ray}}$ reduced in the range between $R_{\text{max}} \approx 550$ μm and $R_{\text{max}} \approx 650$ μm , and increased again after that. This is associated with the bipolar property of the rarefaction wave.

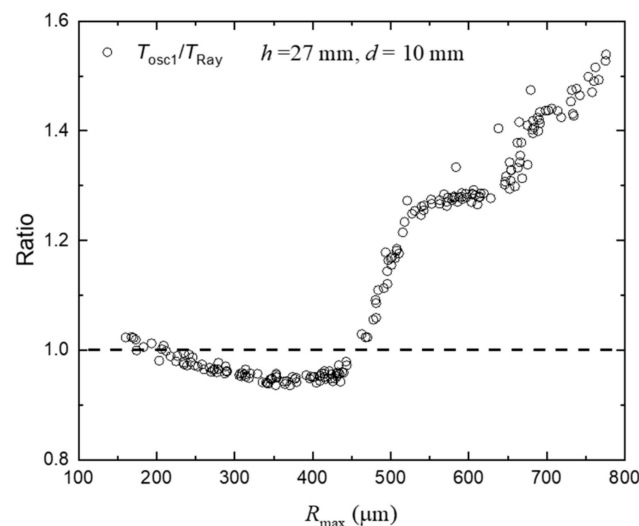


Figure 3. The ratio of $T_{\text{osc1}}/T_{\text{Ray}}$ as a function of R_{max} for the case $d = 10$ mm and $h = 27$ mm.

Laser bubble expansion and its induced liquid-mass oscillation along the free surface in the confined finite liquid produce pressure rises within the liquid, which deform the elastic walls and lead to wall vibrations [23,25]. The alternating stretching and then the compression of the wall resulted in a series of extra vibrational rarefaction waves within the liquid, as shown in Figure 4. It was the initial tensile part of each rarefaction wave induced by outward stretching of the wall that led to the prolongation and re-oscillations of the laser bubble and to the periodic expansion of pre-nucleated secondary bubble clouds along the laser path. Subsequent tensile waves, triggered by liquid-mass oscillation-induced wall vibrations, drive the re-oscillations of the laser bubble and the subsequent initiation of secondary bubble clouds. The superposition of adjacent waves is negligible because the vibrational rarefaction wave decays fast [23].

The vibrational rarefaction waves under investigation exhibit frequencies around 10 kHz [23,25], which surpasses the response capabilities of the transducer used for direct oscillation time measurements of the laser bubble via shock wave signals. However, their critical characteristics can be deduced from the dynamics of the laser bubble and subsequent secondary cavitation.

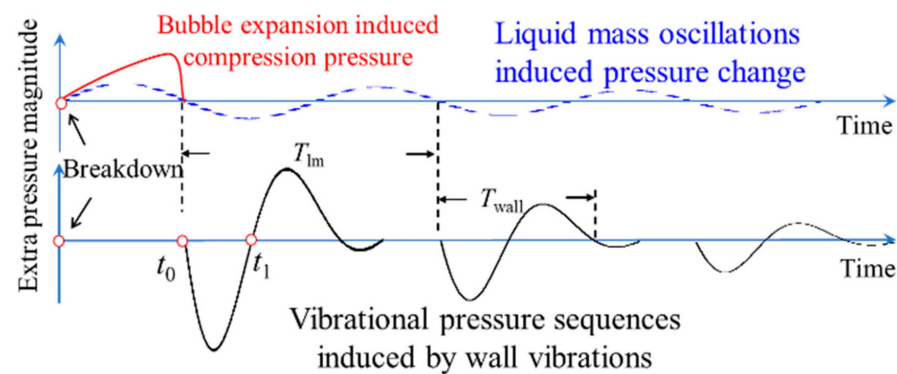


Figure 4. Schematic diagram of the extra pressure wave generation for laser-induced cavitation in the partially confined finite liquid with elastic walls, including bubble expansion-induced compression wave, liquid-mass oscillation-induced pressure change, and wall vibration-induced rarefaction waves.

The eigenperiod of liquid-mass oscillations (T_{lm}) is equivalent to the time interval of each vibrational rarefaction wave, as shown in Figure 4. Given that each secondary bubble cloud is driven, respectively, by the initial tensile part of the individual vibrational wave, it can be deduced from the peak-to-peak interval of adjacent secondary bubble clouds. Figure 2c depicts the evolution of the total area of secondary bubble clouds (A_{tot}) on the upstream side of the laser bubble, which reached a first peak at 103 μs and a second peak at 227 μs , ultimately determining T_{lm} of 124 μs .

Considering the almost constant inception time of the first rarefaction wave, the rebound process of the laser bubble will suffer from different parts of the first rarefaction wave with increasing T_{osc1} , leading to the modulation of R_{max2} and T_{osc2} . Therefore, the eigenperiod of the wall vibrations, T_{wall} , is equivalent to the period of the vibrational rarefaction wave, which can be determined from the modulation of R_{max2} (T_{osc1}) and found to have a value of 80 μs , as shown in Figure 5(b-I).

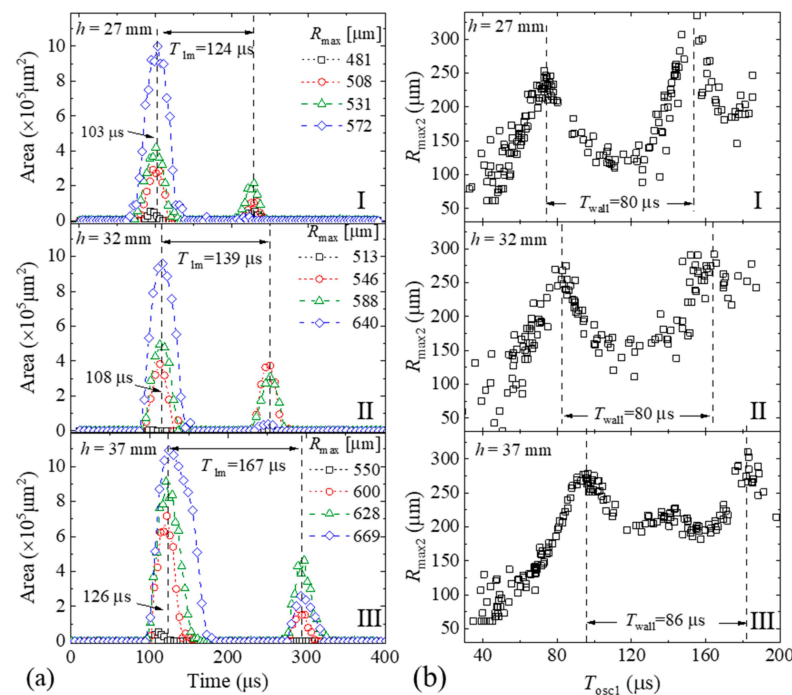


Figure 5. The temporal evolution of secondary bubble clouds (a) and the evolution of R_{max2} concerning T_{osc1} (b) for 10 mm inner-sized cuvette with different liquid heights (I: 27 mm; II: 32 mm; III: 37 mm).

In the case of a relatively large laser bubble, it is noteworthy that the secondary bubble clouds reach their peak area right around the point in time where the vibrational rarefaction wave transitions from negative to positive (t_1 in Figure 4), marking a crucial phase. By considering this, the approximate onset time of the wave (t_0) can be deduced by $t_0 = t_1 - T_{\text{wall}}/2$, resulting in a value of 63 μs for this specific case where $d = 10$ mm and $h = 27$ mm (here $t_1 = 103$ μs and $T_{\text{wall}} = 80$ μs were calculated from Figures 2c and 5a, respectively). The calculated t_0 is closely matched to the T_{osc1} of the laser bubble when the ratio $T_{\text{osc1}}/T_{\text{Ray}}$ reaches a minimum with increasing bubble size, confirming the calculation accuracy. It is worth mentioning that this value closely aligns with the simulated value of 60 μs from a previous study conducted under similar experimental conditions [23], further underscoring the validity and reliability of this methodology.

In general, the parameters of vibrational rarefaction waves, including t_0 , T_{wall} , and T_{lm} , can be determined from secondary bubble dynamics in conjunction with the modulation of R_{max2} (T_{osc1}). Therefore, in the subsequent analysis, our primary focus revolves around the temporal evolution of the secondary bubble clouds and the modulation of R_{max2} (T_{osc1}), to delve into the liquid height and cuvette size-related cavitation dynamics.

First, we investigated the influence of liquid height on rarefaction waves and cavitation dynamics, and heights of 27 mm, 32 mm, and 37 mm were employed with the same cuvette. The temporal evolution of the upstream secondary bubble clouds and the change in R_{max2} relative to T_{osc1} are plotted in Figure 5. For different-sized laser bubbles, both the first and second generations of secondary bubble clouds formed within approximate fixed time ranges, indicating a stable time range for the vibrational rarefaction wave generation. It is essential to mention that the time range for the second generation of secondary bubble clouds might become disrupted for exceptionally large laser bubbles, due to the shift in the coupling between the laser bubble oscillations and liquid-mass oscillations, which was discussed in our previous work [25] but falls outside the scope of the current study. This study showed that the time for the first peak of A_{tot} to be reached increased from 103 μs for $h = 27$ mm to 108 μs for $h = 32$ mm, and further to 126 μs for $h = 37$ mm. Correspondingly, the intervals between adjacent peaks increased from 124 μs for $h = 27$ mm to 139 μs for $h = 32$ mm, and finally to 167 μs for $h = 37$ mm, as displayed in Figure 5a.

Despite the maxima peaks of R_{max2} being shifted towards the right with increasing liquid height, the modulation period of R_{max2} (T_{osc1}) remained constant at a value of 80 μs for $h = 27$ mm and 32 mm, with a slight increase to 86 μs for $h = 37$ mm, as shown in Figure 5b.

In general, with the increase in the liquid height within the same cuvette, the laser bubble showed an approximate constant modulation period of R_{max2} (T_{osc1}) and the secondary bubble clouds depicted a remarkable increase in the time interval between adjacent generations. This indicates the change in liquid has a strong influence on the interval of adjacent rarefaction waves while barely influencing the period of each rarefaction wave.

Next, the influence of the cuvette's inner size on the rarefaction waves and cavitation dynamics was studied. In this case, the liquid height was maintained at a constant value of 27 mm, while the inner size of the cuvette varied from 10 mm to 12 mm. This adjustment simultaneously introduced changes to both the properties of the elastic wall and the liquid mass. The comparison of the secondary bubble dynamics and the variations in R_{max2} (T_{osc1}) between these configurations is shown in Figure 6.

With the progressive increase in the cuvette's inner size, we observed a significant augmentation in both the peak-to-peak intervals for secondary bubble clouds and the modulation period of R_{max2} (T_{osc1}) for the laser bubble. Specifically, for cuvettes with inner sizes increasing from 10 mm to 11 mm and 12 mm, the peak-to-peak interval increased from 124 μs to 144 μs and 162 μs , while the modulation period of R_{max2} (T_{osc1}) increased from 80 μs to 100 μs and 116 μs , respectively. The changes in the modulation period with cuvette inner size indicate that the wall determines the period of each vibrational rarefaction wave. As for the increase in the peak-to-peak interval, it can be attributed to the increase of the liquid volume.

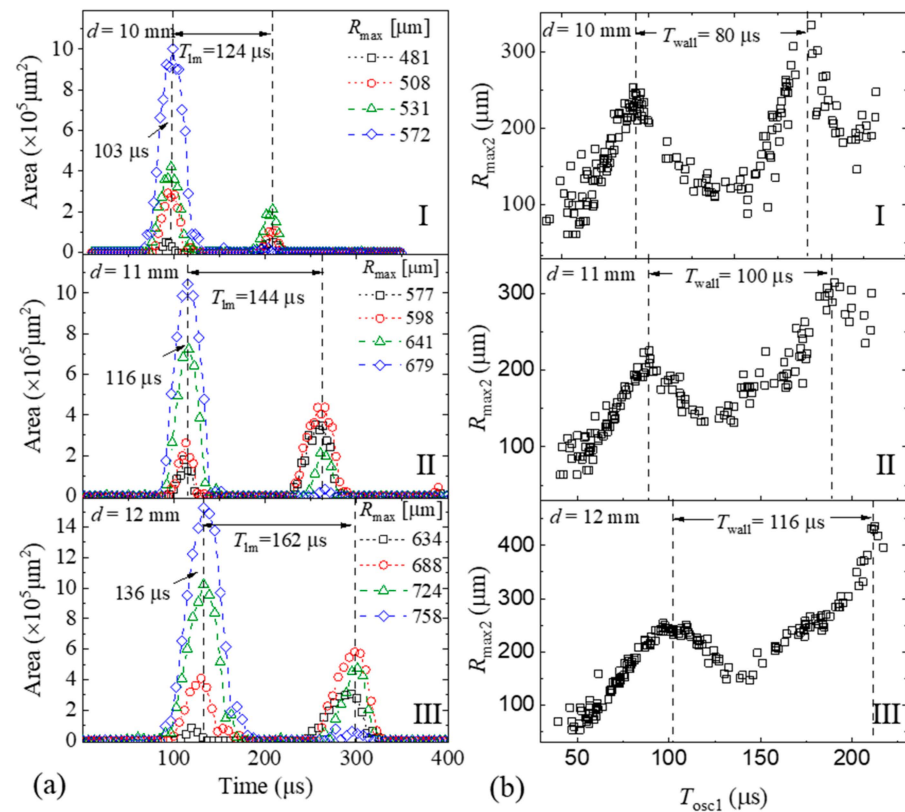


Figure 6. The temporal evolution of secondary bubble clouds (a) and the evolution of $R_{\text{max}2}$ concerning $T_{\text{osc}1}$ (b) for cuvettes with different inner sizes. $h = 27$ mm. I for $d = 10$ mm, II for $d = 11$ mm, and III for $d = 12$ mm. Here, the T_{lm} and T_{wall} in the case of $h = 27$ mm/ $d = 12$ mm were mentioned in [25].

The onset time of vibrational wave t_0 changes in both cases. For the case with varying liquid height in the same cuvette, it increased from $63 \mu\text{s}$ for $h = 27$ mm, to $68 \mu\text{s}$ for $h = 32$ mm, and finally to $83 \mu\text{s}$ for $h = 37$ mm, respectively. For the case with varying cuvette size under the same liquid height, it increased from $63 \mu\text{s}$ for $d = 10$ mm to $66 \mu\text{s}$ for $d = 11$ mm and $78 \mu\text{s}$ for $d = 12$ mm. This indicates a strong relevance between the onset time of the tensile rarefaction wave and the liquid parameters.

Table 1 provides a summary of the key vibrational rarefaction wave parameters associated with the cuvette size and the liquid volume. Our findings demonstrate that T_{wall} is predominantly influenced by the cuvette wall, whereas t_0 and T_{lm} are mainly influenced by the liquid. These observations underscore that the vibrational pressure series directly originates from the periodic vibrations of the wall, which are consistently triggered by the pressure elevation resulting from the expansion of the laser bubble and the subsequent oscillations in the surrounding liquid.

Table 1. Characteristic parameters of vibrational rarefaction waves corresponding to the wall and liquid.

Cuvette Inner Size d (mm)	Liquid Height h (mm)	Liquid Volume V (mm^3)	Vibrational Rarefaction Wave Parameters		
			t_0 (μs)	T_{wall} (μs)	T_{lm} (μs)
10	27	2700	63	80	124
10	32	3200	68	80	139
10	37	3700	83	86	167
11	27	3267	66	100	144
12	27	3888	78	116	162 [25]

For a damped vibrating structure, its eigenfrequency is determined by inherent characteristics such as quality, stiffness, geometry structure, and damping coefficient. When

simplifying it to a one-dimensional mass–spring–damper model, the eigenperiod is positively related to the mass and damping coefficient [45]. Consequently, in this work, an increase in the liquid volume (mass) directly leads to a lengthening of the period of liquid-mass oscillation. This, in turn, resulted in an increased time interval between the adjacent waves. However, it is noteworthy that the eigenperiod of vibrational pressure remains approximately constant because the same cuvette is used, and the slight increase observed in T_{wall} for $h = 37$ mm case may be linked to a minor rise in the damping coefficient of wall vibrations induced by the increased liquid height. This can explain the approximate constant modulation period of $R_{\text{max}2}(T_{\text{osc}1})$ and the increase in the peak-to-peak interval between adjacent secondary bubble clouds. On the other hand, the increase in cuvette inner size with the same liquid height is accompanied by both the increase in the mass of the cuvette wall and the liquid. Consequently, this leads to the increase in the eigenperiods of both the wall vibrations and liquid-mass oscillations and thus to both the increase in the period of each rarefaction wave and in the time interval between adjacent waves.

It is important to highlight that when comparing two scenarios—one with $d = 10$ mm/ $h = 37$ mm and the other with $d = 12$ mm/ $h = 27$ mm—the latter case, even though it possesses a larger liquid volume of 3888 mm^3 , shows a shorter period of liquid-mass oscillation when compared to the former case with 3700 mm^3 . This discrepancy can be attributed to the significant alteration in the liquid geometry, underscoring the crucial role it plays in determining the eigenperiod of the liquid-mass oscillation system, which has multiple degrees of freedom [45].

Another intriguing aspect is the variation in the onset time of the first vibrational pressure concerning liquid parameters. Remarkably, in all the cases, its value closely approximates to half of T_{lm} . This observation implies that the inception of the first vibrational rarefaction wave, which was initially thought to be directly triggered by the compression pressure due to bubble expansion and breakdown shock wave in confined conditions [23], is also associated with liquid-mass oscillations. Specifically, the expansion of the laser bubble initiates liquid-mass oscillations, and each pressure increase driven by these oscillations propels the outward movement of cuvette walls, resulting in a sequence of vibrational rarefaction waves, as shown in Figure 4. For large laser bubbles, the first appearance of compression pressure was significantly amplified owing to the superimposition of the pressure rises induced by liquid-mass oscillations and laser bubble expansion. This, in turn, results in a more pronounced wall vibration than the subsequent series of vibrations. Consequently, the first vibrational rarefaction wave exhibits a more robust tensile component compared to the others with increasing laser bubble size. Moreover, the initial tensile phase of each vibrational rarefaction wave may also be further reinforced directly by the tensile pressure induced by liquid-mass oscillation.

Considering the intricate structures of both the walls and the liquid, it is reasonable to assume that they possess multiple eigen-oscillation modes. The shift in the eigen-oscillation mode of liquid-mass oscillation was confirmed through the variation in the time interval between adjacent secondary bubble dynamics as $T_{\text{osc}1}$ increases [25]. However, detecting the change in the eigen-oscillation mode of the cuvette wall using current methods remains a challenge. The use of interference techniques for directly detecting wall motion offers a potential avenue for measurement and will be explored in future investigations.

In general, this work involves several key mechanisms behind the generation of additional vibrational pressure waves. First, the expansion of the bubble leads to extra compression pressure due to confinement. Furthermore, bubble expansion triggers the oscillation of the liquid with finite volume, resulting in another pressure fluctuation within the liquid. Together, it can induce damped vibrations in the surrounding walls, ultimately giving rise to a sequence of vibrational rarefaction waves with strong tensile components. Such vibrational tensile waves were enhanced due to their superposition with the tensile part of the liquid-mass oscillation-induced wave, thereby significantly altering the dynamics of the laser bubble and driving the expansion of secondary bubbles. Although only cuvette wall size and liquid volume on the vibrational rarefaction waves are confirmed in this

work, it is reasonable for us to deduce that the rarefaction wave generation and resulting complex bubble dynamics also can be influenced by other properties of the wall and the liquid, such as the geometry and material as well as the mechanical properties, since all of these are associated with the system's eigen-frequency.

4. Conclusions

Laser-induced plasma-mediated cavitation within a finite confined liquid, bounded by elastic walls, gives rise to the generation of a vibrational rarefaction wave series within the liquid, exerting a substantial influence on bubble dynamics. This study delves into the impact of cuvette walls and liquid geometry on the formation of vibrational rarefaction waves via monitoring the dynamics of both the laser bubble and secondary bubble clouds, employing high-speed photography and acoustic measurements.

Our findings reveal that, with increases in either liquid height or cuvette wall inner size, both the inception and the peak-to-peak interval of the secondary bubble cloud series experience augmentation. However, the modulation period of $R_{\max 2}(T_{\text{osc1}})$ remains almost constant with varying liquid height and increases with alterations in cuvette inner size. These observations solidify the notion that the vibrational rarefaction wave series is directly induced by wall vibrations, which are intimately connected to laser bubble oscillation and its induced liquid-mass oscillations.

The characteristics of the vibrational pressure series, including its onset time, period, and time intervals, are determined by both liquid-mass oscillations and wall vibrations, as well as laser bubbles. This complex oscillatory system with multiple degrees of freedom offers various means for changing the eigen-oscillations of walls and liquids, including adjustments to their geometry, material properties, and even the location of laser-induced breakdown. This flexibility provides a versatile method for controlling the generation of extra rarefaction waves within the liquid and, in turn, achieving control over the dynamics of laser-induced plasma-mediated cavitation in liquid. Such control holds significant promise in improving efficiency and mitigating side effects in the treatment of cardiovascular laser plaque.

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