BUBBLE STRUCTURES IN ACOUSTIC CAVITATION: OBSERVATION AND MODELING OF A "JELLYFISH"-STREAMER

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ABSTRACT
Most applications of high power ultrasound in chemical processing and cleaning are based on energy concentration by strong bubble collapses. Utilized effects are mainly surface erosion, microstreaming, and free radical production. In typical resonator set-ups cavitation bubbles form structures (streamers) that are distributed inhomogeneously in space, which usually is a drawback for applications. The pattern formation processes are still not completely understood. Detailed observation and classification of streamers is necessary to get more knowledge about the underlying mechanisms. The paper presents recent results on a particular acoustic cavitation bubble structure that appears in different resonator cells. Pictures of this structure, that has the form of a jellyfish, are presented and a possible explanation is given on the basis of a multibubble simulation approach.

INTRODUCTION

Structure formation of acoustic cavitation bubbles [1-3] is observed in many applications of ultrasound in liquids. It is well known that primary and secondary Bjerknes forces, acting on the bubbles, contribute to the emergence of bubble filaments and clustering. However, the details of the bubble interaction seem to be more complicated than the standard text book formulation [1]. Indeed, thorough investigations sometimes show features quite unexpected from the classical point of view. For example, a common expectation is to find (i) the acoustic cavitation bubble sources as well as (ii) the locations of clustering at regions of maximum pressure amplitude in a standing wave field (the pressure antinodes). The reasoning for (i) bases on the fact that bubble germs consisting of stabilized microbubbles or gas pockets at dust particles are presumably expanded beyond the surface tension limit (Blake threshold) at large negative pressures, and (ii) is supported by the phenomenon that bubbles smaller than resonance size are typically attracted by the antinodes. Discrepancy from the above assumptions may nevertheless occur and can be explained by, for instance, bubble nuclei not homogeneously distributed in space, or by strongly nonlinear bubble oscillations.
In the following we report on the observation of a particular double layer bubble structure, emerging in standing wave fields of sufficient power at 20 to 50 kHz, where the antinodes seem to be neither the origins nor the destinations of bubbles. Rather unexpectedly, the pressure amplitude maxima appear to be void of cavitation. In a simulation we try to mimic the observed structures.

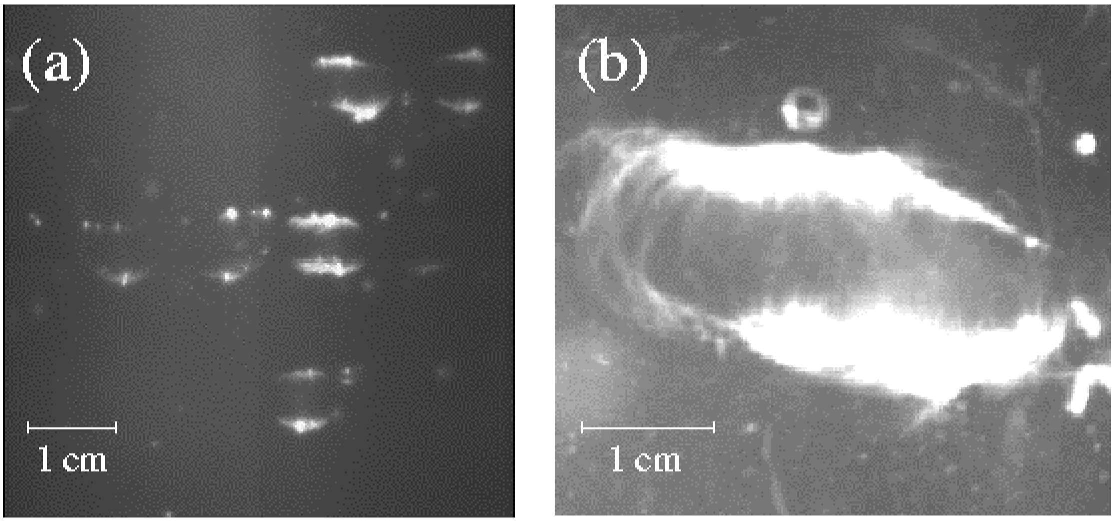

Fig.1: Layered cavitation bubble structures ("jellyfishes") in acoustic standing wave fields. (a): 40 kHz driving, picture width approx. 6 cm. (b): 25 kHz driving, picture width approx. 4 cm.

OBSERVATIONS

Figure 1(a) shows a snapshot photograph of bubble structures in a transparent 40 kHz resonator (side view; bubbles appear bright as they reflect the light). Double layers of bubbles can be observed that essentially reproduce the relatively well established standing wave field in the cuboid container of 20 cm(l) x 16 cm(w) x 15 cm(h). Very similar patterns can be observed in a smaller cuvette (16 cm x 9 cm x 9 cm) driven at 25 kHz, see Fig. 1(b) for a single object. In high-speed recordings the structures from Fig. 1(a) resembled jellyfishes, which became our internal name for the double layer objects. The closer view in Fig. 1(b) reveals that the upper and lower layers appear to be connected by threads of bubbles. It turns out, however, that a double layer is located symmetrically to a pressure nodal plane, which is typically not crossed by bubbles. The top and the bottom part of the structure are rather separate units, and bubbles originate near the nodal plane and travel either to the top or the bottom part. This is better resolved in Fig. 2, where a sequence from a high-speed movie is shown. Additionally, it can be seen that the two parts oscillate in antiphase, i. e. the corresponding bubbles reach their maximum and minimum volumes at alternating times. This phase jump is characteristic for the excitation in a standing wave if a pressure node is crossed. The pressure antinodes are situated roughly halfway between the upper layer of a structure and the lower layer of the next structure above in Fig. 1(a), and approximately at the top and bottom of the picture in Fig. 1(b).

Fig. 2: Three pictures from a high-speed movie (2250 frames/sec; background 1 microsecond flash illumination; picture width approx. 1 cm each). The double layer has been "attached" to a hypodermic needle to better fix it in space for recording. The beat between flash light frequency and acoustic driving frequency highlights the antiphase oscillation of top and bottom part of the structure.

The antinode regions appear to have a very low, if any, bubble population. This is in spite of measured pressure amplitudes in the range of 200 kPa and above. The bubbles develop somewhere near the nodal planes and move towards the antinodes, but cluster half way in the layered structures. From top the layers look dendritic with a central aggregate like a root, compare Fig. 3(c).

SIMULATIONS

The observations have been reproduced qualitatively by a “particle” simulation. In this model, many individual bubbles are subjected to calculated forces in an acoustic standing wave field, where the influence of primary [1,2,4] and secondary [1,2,5] Bjerknes forces, viscous drag force, and added mass are taken into account. The calculations are based on nonlinear spherical bubble oscillations, and the forces vary according to the variation of the driving pressure in the standing wave field (compare [6]). Bubbles can be created and annihilated, e.g. by collision with another bubble.
In this type of simulation, the choice of bubble nucleation sites is crucial. We generated 100 bubbles at random sites on two rings near the pressure nodal plane, and the maximum pressure amplitude was 200 kPa at the antinodes. Bubble sizes have been held constant at equilibrium radii of 10 micron. For these bubbles, the antinodes are repulsive at the indicated pressure [4]. Thus, the clustering, initiated by the secondary Bjerknes force, occurs between node and antinode. A curved dendritic double layer emerges.

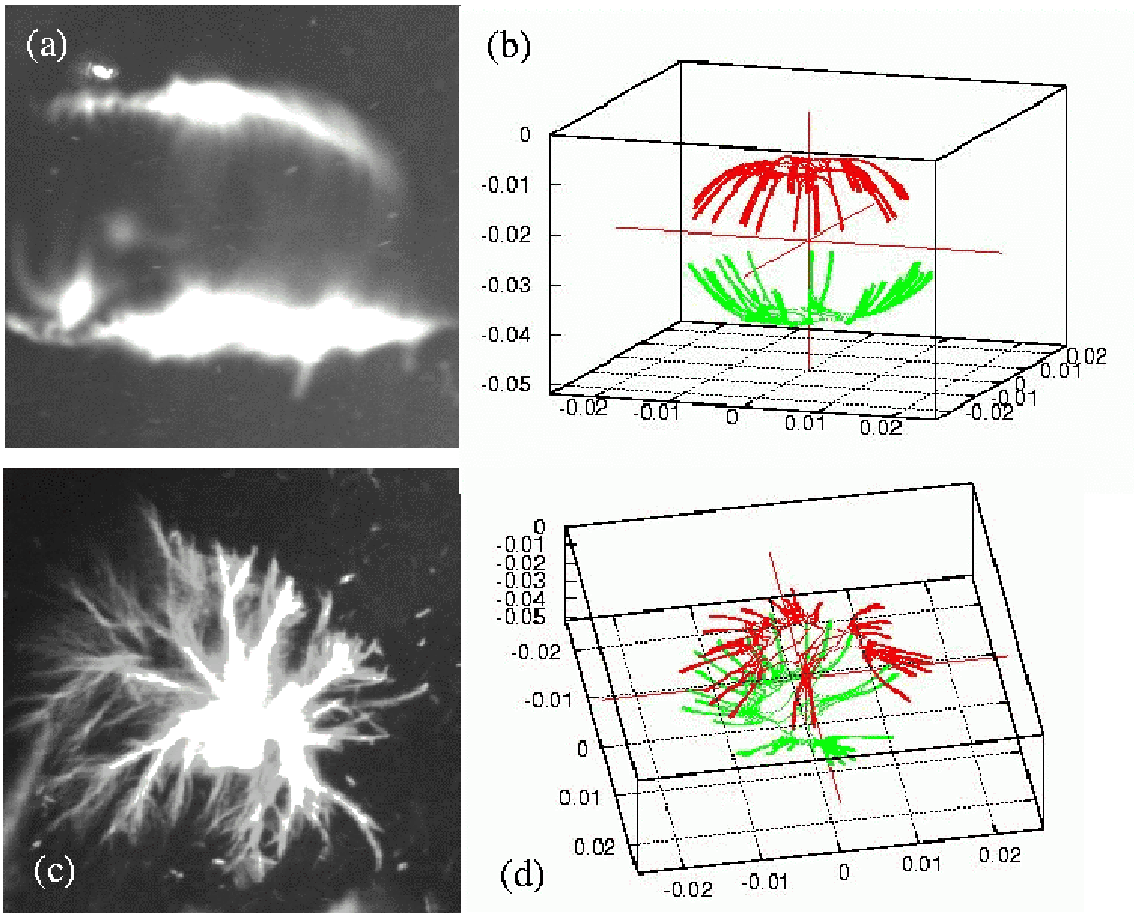

Fig. 3: Side view of jellyfish streamers from experiment (a) and simulation (b), and the corresponding top views, (c) and (d). The simulation is in scale to the observed pictures. The origin of the coordinates marks a pressure antinode, the hair cross the point of pressure amplitude symmetry in the nodal plane.

SUMMARY

We have presented a particular cavitation bubble structure that has been observed in various standing wave resonators. The “jellyfish” structure consists of two dynamic bubble layers arranged symmetrically with respect to a pressure nodal plane. Each layer is mainly concentrated between the pressure nodal plane and the adjacent antinodes. The bubbles appear to originate in or near the nodal plane and travel towards central agglomerates within the layers. Few or no bubbles have been observed near the antinodes.
Simulations by a particle approach can model the bubbles' behaviour qualitatively if their generation points are placed on rings near the nodal plane. Although details of the structures (like the fine dendrites and the massive central clustering) are not perfectly captured by the model yet, main features are reconstructed. The absence of bubbles at the pressure antinode is caused in the model by the (nonlinear) repulsion [4] and an inhomogeneous bubble source distribution in space. The latter feature has been transferred from the experimental observation to the simulation. The underlying mechanism, however, is still not clear. Future observations and theoretical investigations should give more insight to this issue.

LITERATURE

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