Early stage of bubble dynamics and luminescence in water in a converging shock reflected by a free surface

G. SANKIN[1,2], R. METTIN[2], R. GEISLER[2], V. TESLENKO[1], W. LAUTERBORN[2]
[1]Lavrentyev Institute of Hydrodynamics,
pr. ac. Lavrentieva, 15, 630090, Novosibirsk, Russia
[2]Drittes Physikalisches Institut, Universität Göttingen
Bürgerstr. 42-44, 37073 Göttingen, Germany

The focusing and reflection of an acoustic shock wave in water near a free surface and the induced cavitation is investigated experimentally. Ultra high speed photo recording and high resolution pressure and light emission recording is used. The results reveal the shock wave – bubble interaction resulting in secondary cavitation waves. The correlation between bubble dynamics and luminescence is observed.

Applications of acoustical shock waves in liquids range from lithotripsy to the transport of chemicals into biological cells [1], and the detailed conditions of a shock and accompanying phenomena are still under investigation. If a shock wave in liquid hits a free surface or an acoustically soft reflector, the pressure in the reflected wave is inverted and has a strong negative pressure component near the boundary. Significant nonlinear phenomena have been observed for this case, for instance the reflection of a positive shock by a free surface causes cavitational breakdown accompanied by secondary acoustic waves [2]. Preliminary investigations showed light emission from water and glycerin solutions under this condition [3], but were limited by the high sound speed in water and in the small cavitation area. In this paper more detailed observations of wave propagation and of bubble dynamics as well as light emission are presented.

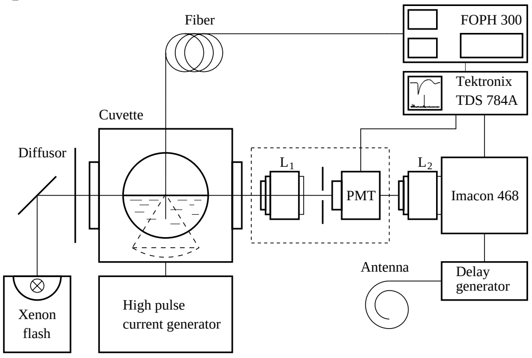

Fig. 1: *Experimental setup (dashed box optional).*

In Fig. 1 a sketch of the experimental setup is shown. An electromagnetic generator (current pulse of 0.8 μs rise time) based on the principle from [4] is used. The tranducer has an aperture of D = 70 mm, and the curvature radius of 55 mm determines the focal distance F = 55 mm. It is installed at the bottom of a cubic Kaprolon (kind of polyamide) cuvette with glass windows (11 cm between the inside surfaces of the windows). The pressure in the shock focus can be controlled via the generator voltage U_g from 5 to 10 kV on a capacity of 2 μF. We used distilled, demineralized water, saturated with gas at room temperature. Pressure disturbance measurements were done with a fiber optic hydrophone (FOPH 300, 150 μm diameter, 7 ns rise time [5]). The glass fiber position is referred to the shock focal point at z = 0 mm, which was determined as the maximum of pressure amplitude. To observe shock wave propagation and bubble dynamics an ultra high-speed camera (IMACON 468, Hadland, 10 ns exposure time, 8 frames) with a xenon flash lamp with diffusor is used. The light emission is recorded resolved in space and time by a PMT (Hamamatsu R5600U-06, spectral range from 300 to 530 nm, 2 ns rise and fall time). For this purpose, the focal area of the cuvette is focused in scale 1:0.8 on a diaphragm with a slit l_v = 1 mm in vertical and l_h = 2 mm in horizontal direction by a 50 mm objective (Nikon). Hence, the timing uncertainty between shock wave and light is limited to $1.2\, l_v / c_0 = 0.8\,\mu$s, where $c_0 = 1.5\,\mu$m/μs is the sound speed in water. The signal is recorded using a fast oscilloscope (TDS 784A, Tektronix, 1 GHz).

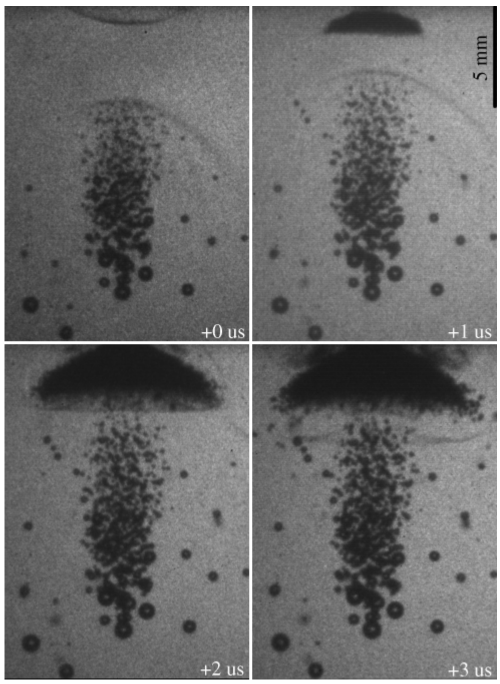

Fig. 2: *Shock-wave-induced breakdown in water near a free surface (on top), U_g = 9 kV.*

Since the membrane is shaped as a sphere segment, a converging acoustic pulse is generated in the liquid. It reaches the maximum pressure in the focal point whose location negligibly depends on the voltage. The cavitation occurs after the negative pressure component.

In a first series of experiments the shock is focused exactly on the free surface at z = 0 mm. The direct primary wave produces an elongated (cigar shaped) cloud of larger bubbles below the focal point, and the reflected primary wave produces a fog-like cloud of very small bubbles with the shape of a (probably hollow) cap directly under the surface (Fig. 2).

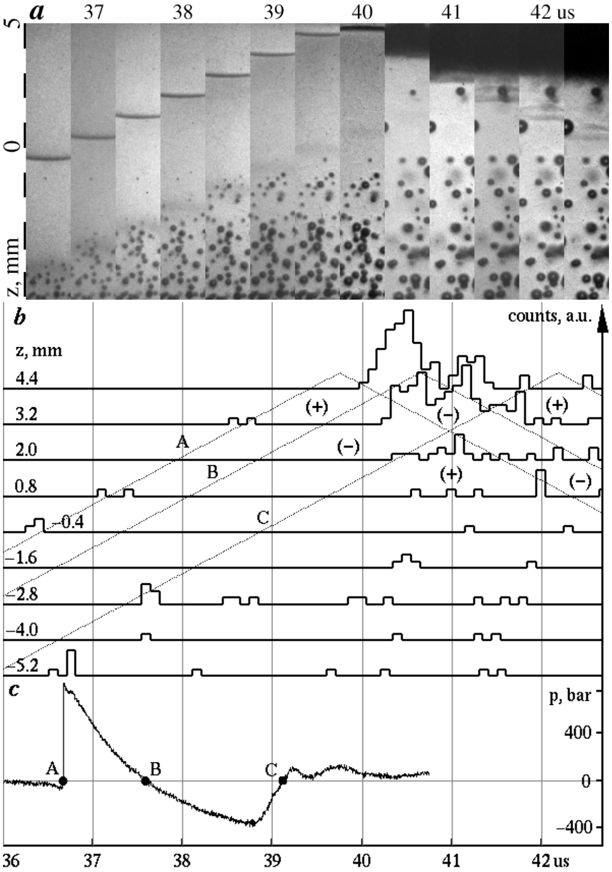

Fig. 3: *Time correlation between pressure disturbance, bubble dynamics and luminescence in water, free surface at z = 5 mm. (a): Streak images for 8 kV. (b): Luminescence histogram for 8 kV at equidistant z from -5.2 mm to 4.4 mm and wave traces extracted from the streak image (A - primary wave front, B - expansion wave front C - secondary wave front, '+' and '–' indicate the pressure sign on the z-axis for a non-cavitational regime. (c): Pressure for 7 kV, z = 0 mm (focal point); at the times A, B, and C the pressure equals to zero.*

In a second series of experiments the free water surface was at z =5 mm above the focal point. Hence, a space gap between the elongated and the cap like bubble clouds occurs and pressure measurements in this part of the liquid are possible without cavitation. The results of the experiment are presented in Fig. 3. The streak image (Fig. 3a) is assembled from two series of Imacon images clipped to 1.8 mm width around the symmetry axis of the process. The light statistics (Fig. 3b) is collected for 32 shots for each equidistant vertical position z from -5.2 mm to 4.4 mm of the center of the slit. The count of single PMT pulses are presented as histogram (100 ns bin width) in linear units (78 pulses have been counted for z = 4.4 mm). The traces of the waves extracted from the streak images are drawn in the same plot to synchronize the luminescence to the pressure disturbances. A pressure trace measured with the FOPH is shown in Fig. 3c. The measurement in the focus reveals an additional pressure rise after the negative pressure component that corresponds to the secondary wave on the streak image.

Near the free surface light emission takes place as two groups of flashes immediately after the shock. The second group of flashes corresponds to collision of the reflected front of the primary wave (A) with the secondary wave (C) as one can see on the streak image. This light is distributed over the uppermost slit positions (z > 1 mm) which might be due to diffraction of light in the cap shaped bubble cloud. From the water in the range of z from 0.2 mm down to -2.2 mm less light is observed. Below z = -2.2 mm flashes from bubbles expanded in the rarefraction (BC) and collapsing in the secondary wave (C) are recorded. The light pulses from water in the primary compression wave (AB) is due to bubbles remaining from previous shots, which had not enough time to leave the liquid or dissolve. The intensity of this light could be increased by the decrease of the delay between shots.

The results of high speed photo-recording and pressure measurements show only an insignificant increase of pressure in the focus with an increase of the generator voltage U_g. The pressure near the focus (negative z) increases approximately as $1/|z|^{1.25}$ and is limited by nonlinear processes, namely Mach stem formation and cavitation. Higher pressures could be produced by different generators with higer D/F ratio [6] or with half- or full-sphere transducers built as multicenter discharge generators [7]. The secondary wave is found to be most probably due to cavitation, i.e. to relaxation after breakdown and to shocks from bubble collapses in a manner as described in [8]. Also the measured luminescence seems directly connected to bubble collapses. We have been able to increase the light output by addition of glycerin (different molecular forces) and by a decrease of temperature (decrease of saturation vapor pressure), as has been reported in other sonoluminescence experiments. These changes are expected to vary the cavitational effect in a way to amplify the secondary shocks as well.

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