ULTRASONIC CAPILLARY EFFECT AND SONOLUMINESCENCE

N.V. Dezhkunov[+], A. Francescutto[#], P. Ciuti[*] and P. Ignatenko[+]
+ Belarusian State University of Informaics and Radioelectronics, Minsk, BELARUS
# DINMA, University of Trieste, via A.Valerio 10, 34127 TRIESTE, ITALY
[*] *Physics Department, University of Trieste, via A.Valerio 2, 34127 TRIESTE, ITALY*
dnv@bsuir.edu.by

*

Abstract

Experimental results described in the present paper confirm the hypothesis about cavitational nature of the ultrasonic capillary effect (UCE), which is an abnormally high rise of a liquid in a capillary under the action of ultrasound. In accordance with this hypothesis UCE is associated with the collapse of cavitation bubbles at the capillary entry. Bubbles collapse asymmetrically to form a jets directed to the capillary but-end. By getting into the capillary channel, every such a jet increments the height of the capillary rise. When summed up these increments result in the experimentally observed increase of the height and speed of the liquid rise in the capillary. Theoretical estimations based on this mechanism are in acceptable agreement with experimental results.

Introduction

The ultrasonic capillary effect (UCE) is an increase of the liquid rise in a capillary tube under the action of ultrasound [1, 2]. It can be demonstrated by the following simple experiment (Fig. 1). Place the capillary tube into the vessel equipped with the ultrasonic emitter.

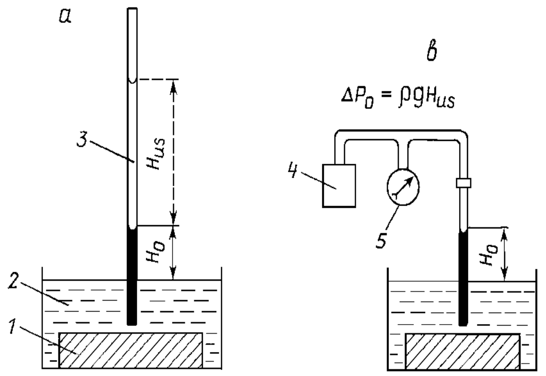

Figure 1 : a) set-up for measurements of H_{US} (a) and for measurements of excess pressure ΔP_0 (b), (1) ultrasound transducer, (2) liquid, (3) capillary tube, (4) pump, (5) manometer.

Fill the vessel with a liquid. As a result of capillary forces the latter will begin to rise. The liquid stops at the normal capillary rise height H_0. If ultrasonic vibrations are now applied, the liquid will tend to rise to a new height $H^* = H_0 + H_{US}$, where H_{US} is the height of the rise under the action of ultrasound. The H_{us} value in some cases exceeds H_0 by orders of magnitude and is much higher than could be caused by radiation forces and acoustic streaming. Ultrasonic capillary effect can be characterized by the liquid height rise H_{US} (Fig. 1a) or by the excess pressure ΔP_0 over meniscus in the capillary necessary to keep liquid at the height H_0 (Fig. 1b) [1-3]. Normally $\Delta P_0 = \rho g H_{US}$. Different hypotheses have been advanced to explain the nature of this phenomenon. It has been shown that cavitation plays an important role in the generation of the liquid flow directed into the capillary [1-4]. If cavitation cloud sets at the capillary inlet, UCE is observed at any orientation of the capillary in the acoustic field and does not strongly depend on the orientation either.

In this work new results have been received, which confirm cavitational nature of ultrasonic capillary effect and permits to conclude that resulting flow of the liquid into the capillary is formed due to bubbles collapse at the capillary entry.

Experimental

Figure 2. shows the schematic diagram of the experimental set - up.

The test chamber represents a glass cylinder with a diameter of 80 mm and height of 210 mm. It was equipped with a coiled glass tube through which a temperature - controlled liquid was pumped. The source of ultrasound was a piezoceramic transducer with a wave guide, mounted at the bottom of the chamber. Vibrating surface (i.e. ultrasound emitter) of the waveguide was 15 mm in diameter and its resonance frequency was 41.9 kHz. The Non-Contact Vibrometer UVM-3M was used to measure vibration amplitude A of the emitter surface. The standard error in the measurement of A being 4 %.

The procedure of the measurements was as following. The capillary tube was immersed in the liquid and fixed in the prescribed position along the central axis of the chamber by means of a coordinate positioning mechanism. Central axis of the chamber and of the waveguide of the transducer coincided to within ± 0.1 mm. The valve connecting the capillary – manometer – pump system with the atmosphere was opened. Under the capillary forces the liquid in the capillary tube rose to the height H_0. The valve was then closed and the generator was turned on. Under the action of ultrasound at suitable regime of sonification the liquid tended to rise to a new height. The liquid was than restored to its original position H_0 by using a pump to increase the pressure over the meniscus in the capillary.

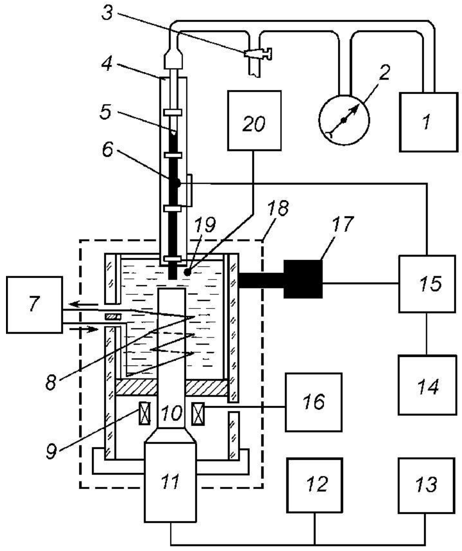

Figure 2 : Schematic of the experimental arrangement. (1) pump, (2) manometer, (3) valve, (4) guide plate of coordinate positioning mechanism, (5) capillary tube, (6) piezoelectric sensor, (7) thermostat, (8) coil, (9) amplitude sensor, (10) wave guide, (11) transducer, (12) frequency meter, (13) generator, (14) computer, (15) oscilloscope, (16) voltmeter, (17) photomultiplier, 18 - light-tight box, (19) thermocouple, (20) galvanometer.

The excess pressure ΔP_0 over the meniscus necessary to keep it at the level H_0 was measured by a manometer. Simultaneously SL intensity was recorded. The measurements of ΔP_0 and L in these experiments were accomplished after 2 minutes of sonification at chosen amplitude. In experiments related to the thresholds measurements amplitude A was increased by stepped ramp. The ramping sequence consisted of increasing amplitude A to a set value for 5 s, then to a higher value for 5 s, etc., until sonoluminescence or ultrasonic capillary effect manifested itself. The step size was 0.1 micron for amplitudes in the range 0-2 microns; and 0.5 microns for amplitudes in the range 2-15 microns.

The temperature was maintained constant within ± 1 °C error limits in experiments with water and acetone and ± 3°C in experiments with glycerin and water-glycerin mixture.

Results

The main result of our experiments is that at ultrasound intensities lower than the SL threshold no increase of the capillary rise have been registered. At small distances d (d < 0.5 mm) the SL and UCE thresholds nearly coincide (table 1) i.e. to within the resolution of the incremental increase of A.

Table 1: Amplitude thresholds for SL appearance ($A_{SL,th}$) and for UCE appearance ($A_{UCE,th}$), microns

Para-meter	Liquid number					
	1	2	3	4	5	6
$A_{SL,th}$	7.0	2.5	1.5	0.7	0.5	0.4
$A_{UCE,th}$	8.5	3.0	1.5	0.9	0.5	0.5

Measurements presented in the table were done at d = 0.05 mm. The liquids in the table are numbered as following: 1 – glycerin, 2 – water-glycerin mixture with 60% (weight) of glycerin and 40 % of water; 3 – water, 4 – chlorobenzene, 5 – isoamyl alcohol, 6 – acetone, t = 25° C. If the capillary entrance is at large distance d (d > 2 mm) the threshold of SL appearance is lower than the threshold of UCE appearance.

Figure 3 shows L and ΔP_0 dependencies on the amplitude A of vibration of the transducer radiating surface. The measurements presented here were done with the capillary positioned at small distance from the radiating surface, d = 0.05 mm. Every point is averaged result of 3 independent measurements. A linear scale has been chosen for ΔP_0 and a logarithmic one for L. Every point is the averaged result of 3 independent measurements and the uncertainty associated with each point is explained later in the discussion of the results.

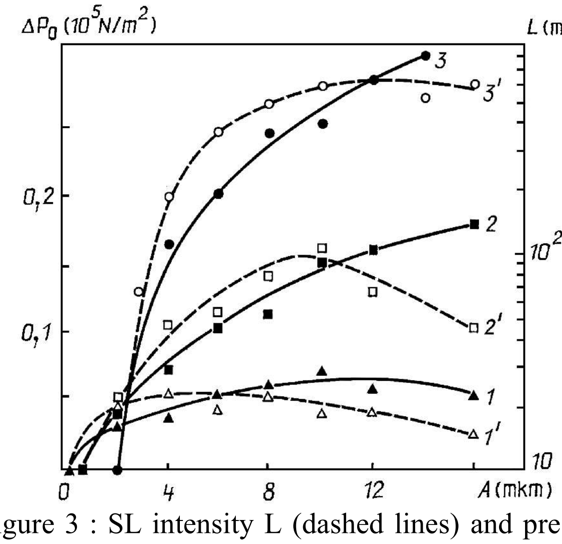

Figure 3 : SL intensity L (dashed lines) and pressure ΔP_0 (solid lines) for different liquids. (1, 1′) aceton, (2, 2′) water, (3, 3′) water-glycerin mixture with 60% (weight) of glycerin and 40 % of water, t = 23°C, distance d between the capillary but-end and the radiator surface is 0.05 mm.

From this figure it is seen that in liquids with higher SL intensity ultrasonic capillary is also higher. SL intensity grows with A, achieves maximum and then tends to decrease. This is in qualitative agreement with results related to studying of the dependence of cavitation activity on ultrasound intensity [5]. ΔP_0 however for water and glycerin – water mixture increases with A in all range of A. For acetone it starts to decrease at A ≈ 12 microns.

Figure 4 shows temperature dependencies of L and of ΔP_0 for d = 0.05 mm.

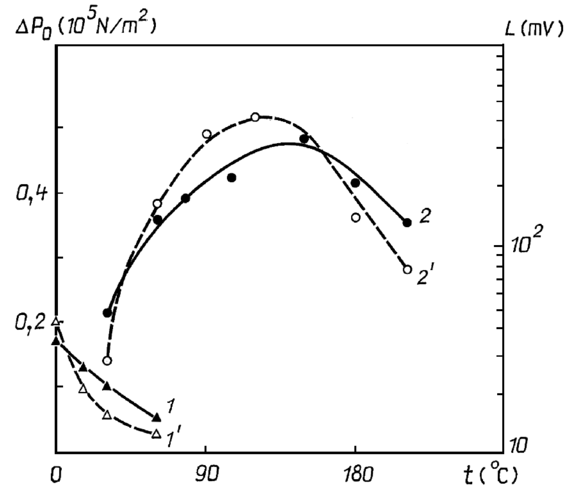

Figure 4 : SL intensity L (dashed lines) and pressure ΔP_0 (solid lines) versus temperature: (1, 1′) water, d = 5 mm; (2, 2′) glycerin, d =0.05 mm; A = 8.5 microns.

For water both L and ΔP_0 decrease with temperature. For glycerin they increase, achieve maximum and decrease by increasing temperature.

Figure 5 shows L and ΔP_0 dependencies on the amplitude of transducer vibration for large distance d.

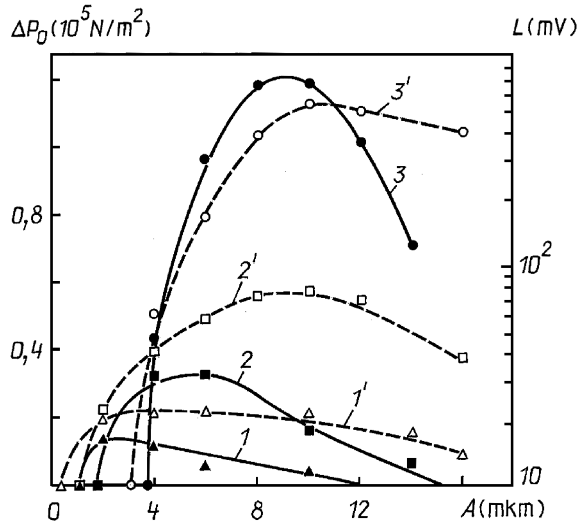

Figure 5 : SL intensity L (dashed lines) and pressure ΔP_0 (solid lines) for different liquids. (1, 1′) aceton, (2, 2′) water, (3, 3′) water-glycerin mixture with 60% of glycerin and 40 % of water, t = 23°C, d = 5 mm.

In this case correlation is not so good as for small d (Figs. 3 and 4). Still those of the liquids which exhibit higher SL intensity also show a greater ultrasonic capillary effect.

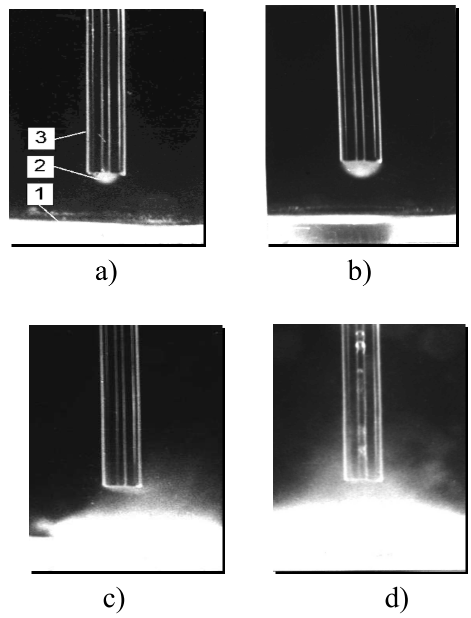

Figure 6 : Cavitation cloud at the capillary inlet at different transducer amplitude A. A = 1 micron (a), 2.5 (b), 6 (c) and 10 microns (d), distance d = 5 mm; (1) radiating surface, (2) cavitation cloud, (3) glass capillary tube.

If the capillary is at large distance d from the emitter a liquid start to rise in the capillary under ultrasound when a cavitation cloud appears at the capillary but-end (Fig. 6). By increasing the vibration amplitude A the size of this cloud is increased as well as its optical density (Fig. 6a, 6b). Optical density is increased evidently because of increasing of bubbles concentration in the cloud. In this conditions UCE also increases. Then the density of bubbles between the emitter and the capillary rise increases as well (Fig. 6c, 6d). In this conditions (6c, 6d) the visible size of the cloud at the capillary diminishes, it starts to dance chaotically on the surface of the but-end. The capillary rise at large A and d becomes unstable. The level of the liquid in the tube starts changing chaotically (sometimes in a jump-like manner) with amplitudes so great that the standard deviation of the measurements of UCE in these conditions is 25% and more and everaged H_{us} decreases significantly. At A not much higher than SL threshold, when the cavitation cloud stays stably at the capillary (Fig. 6a), such large liquid level fluctuations do not occur, and the standard deviation is normally not larger than 10%. At small d (Fig. 4) such fluctuations are not seen for any amplitude. It should be noted that the cavitation cluster at the capillary inlet at low amplitude A (Fig. 6a) seems to be different from clusters presented in classification done in [6].

Discussion of the results

Rather good correlation exists between SL emission and ultrasonic capillary effect (table 1, Figs. 3-6): thresholds of both phenomena nearly coincide for small d; in wide range of amplitudes ΔP_0 grows when SL intensity grows; in liquids producing higher SL emission intensity ultrasonic capillary effect is also higher.

This degree of correlation between the phenomena may be considered as confirmation the hypothesis of a cavitational nature for UCE [2, 14]. In accordance with this hypothesis the mechanism of UCE is as following. Under the action of ultrasound a cavitation zone (or cavitation cluster) appears at the capillary entrance. Cavitation bubbles collapse asymmetrically with the formation of microjets of the liquid. On entering the capillary channel, every such a jet increments the height of the capillary rise by a magnitude ΔH_r. When summed up these increments result in the experimentally observed increase of the height and speed of the rise (or penetration) of the liquid in the capillary channels. The higher the concentration of bubbles at the capillary inlet and the more violently they collapse, the stronger the ultrasonic capillary effect one may expect. The same is true for sonoluminescence in the general sense.

When increasing the amplitude of emitter vibrations transient cavitation appears first at the surface of the emitter. And this is the threshold of both sonoluminescence and ultrasonic capillary effect. Cavitation at large distances d ($d \geq 2$ mm) appears at higher amplitudes. By this reason the UCE threshold is higher in this conditions than the SL threshold (Fig. 5).

Other reason of the differences of the effects is differences in mechanisms, namely peculiarity of UCE mechanism. Within the time interval between two sequential penetrations of the jet into the capillary channel the liquid may flow out of the capillary tube under the gravitational forces or excess pressure ΔP_0 if the latter is applied. The height of the rise, in this case, is reduced by a value ΔH_d before next collapse at the capillary entrance. When statistically averaged ΔH_d becomes equal to statistically averaged ΔH_r the rise stops.

If the concentration of collapsing bubbles is low (ultrasound intensity is not much higher than the SL threshold), the probability of the collapse of the bubble at the capillary inlet is small. So the time interval between sequential collapses is long and the portion of the liquid which entered into the capillary (as a result of the bubble collapse) has time to flow out from the capillary before next collapse. As a result increase of the capillary rise under ultrasound may become very small or zero. At the same very time sonoluminescence is not zero as far as bubbles in the volume of the liquid collapse. This explains why at large d after achieving maximum ΔP_0 comes down much quicker than SL intensity.

Conclusions

It is shown that correlation exists between sonoluminescence from a multibubble cavitation zone and ultrasonic capillary effect. This result confirms the hypothesis about cavitational nature of ultrasonic capillary effect and permits to conclude that resulting flow of the liquid into the capillary is formed due to bubbles collapse at the capillary entry.

Acknoledgements

The research has been supported by the Belarusian Foundation for Fundamental Investigations and by the Consorzio per l'Incremento degli Studi e delle Ricerche degli Istituti di Fisica dell'Universita di Trieste.

References

[1] P.P. Prokhorenko, N.V. Dezhkunov, G.E. Konovalov, "About cavitational mechanism of the influence of ultrasound on the liquid rise in a capillary," Izvestija AN BSSR ser. phys.-- techn.(In Russ.), No 3, 1978, pp. 65 – 71.

[2] N.V. Dezhkunov, P.P. Prokhorenko, "Action of ultrasound on the rise of a liquid in a capillary tube and its dependence on the properties of the liquid," J. Eng. Phys., vol. 39, pp. 1014-1019, 1980.

[3] N.V. Dezhkunov, "Ultrasonic capillary effect: theory, experience and perspectives of applications," (in Russ.), in Proceedings of the 11-th all-Union Conference on Acoustics. Moscow, 1991, section N, pp. 135-138.

[4] N.V. Dezhkunov, T.G. Leighton, "The use of a capillary as a sensor of cavitation," in Proceedings of ISNA 16, Moscow 2002, V. 2, pp. 1163 – 1166.

[5] A. Henglein, R. Ulrich, J. Lilie, "Luminescence and chemical action by pulsed ultrasound," J. Am. Chem. Soc., vol., 111, pp. 1974-1979, 1989.

[6] R. Mettin, D. Krefting, R. Geisler, T. Tervo, P. Koch and W. Lauterborn, "News from the Zoo of Cavitation," presented at WCU 2003, Paris.