Observation and investigation of anomalous X-ray and thermal effects of cavitation

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The anomalous X-ray and thermal processes associated with cavitation of fast liquid jet in a narrow channel and in free space outside the channel are considered. It has been found that the output of the channel and the initial part of the free jet are sources of intense X-rays, generation of which is connected with shock waves. The energy of X-rays ($\hbar\omega \approx 0.7$–5.0 keV) depends on the type of atoms on the radiating surface. Formation of shock waves and X-rays is accompanied by generation of undamped high-frequency thermal waves.

Keywords: Cavitation, X-ray generation, shock wave, heat transfer, undumped thermal waves.

Introduction

CAVITATION is one of the most interesting phenomena in nonequilibrium liquid[1]. This process is associated with the loss of stability of the hollow bubbles that emerge in the liquid when there is an abrupt decrease in the external pressure. Similar processes take place at Coulomb collapse of target[2–4]. Earlier only one radiative effect related with cavitation was known – bubble optical sonoluminescence. This effect is associated with emission of very weak thermostimulated optical radiation of atoms situated in the zone of collapse with temperature $T \approx 2000$–5000 K for multi-bubble sonoluminescence and $T \approx 10^5$ K ($kT \approx 10$ eV) for single-bubble sonoluminescence[1]. Bubble cavitation, collapse and the accompanied formation of a high-power acoustic pulse in the surrounding liquid can be produced by transportation of fast liquid jet through thin channel.

During preliminary investigations of different regimes of cavitation we have observed several anomalous radiative phenomena, not related to traditional description of sonoluminescence: very intense glow of liquid jet[5], controlled X-ray generation with energy $E_x \approx 0.8$–1.1 keV in areas distant (or screened) from the cavitation zone[6,7] and generation of unknown earlier undamped thermal waves[8–10]. The registration of X-rays outside the chamber is surprising because the length of the free path of such X-rays in Plexiglas is no more than a few microns or even fractions of microns. If originated from the cavitation region, the radiation would not pass through the layer of liquid and the chamber walls to the detector. This X-radiation is not the direct result of cavitation processes. Such radiation is not connected with the temperature inside the cavitation region (the temperature in this region is small and $kT \ll E_x$). In particular, the energy of this radiation strongly varies with the type of atoms on the outer surface of the cavitation chamber and increases with the use of atoms of heavier elements[6,7]. The objective of this article is to search for reasons and preconditions of these phenomena in cavitating liquids.

Abnormal X-rays during cavitation of liquid jet

Investigation of cavitation-induced X-ray generation in closed cavitation chamber

The scheme of the experimental set-up for studies of radiative phenomena at cavitation in spindle oil is shown in Figure 1. The total volume of the pumped liquid circulating over a closed loop is 20 litre. The cylindrical operating chamber, 15 cm long and 8 cm in diameter, was made of Plexiglas with wall thickness of ~3 cm. A dielectric partition with a demountable diaphragm and a thin channel ~1 mm in diameter and ~2 cm long was placed at the centre of the chamber. Experiments with pumped

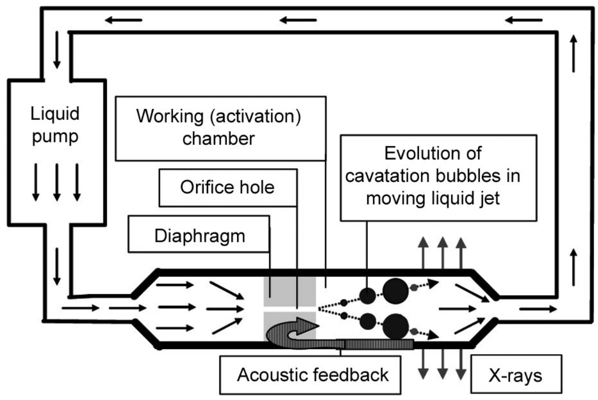

Figure 1. Experimental set-up for the study of radiative phenomena at cavitation in moving spindle oil.

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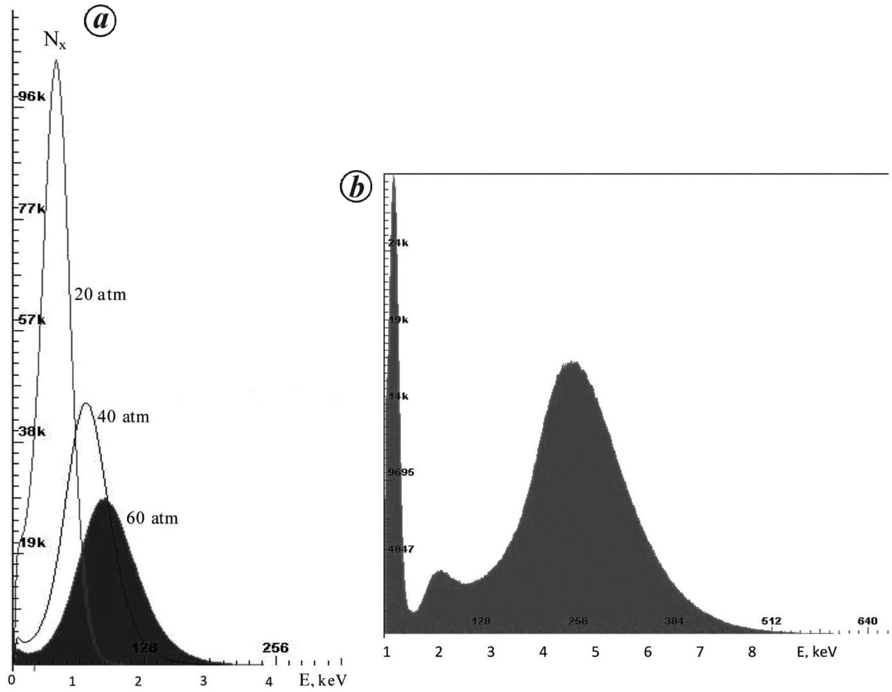

Figure 2. X-ray spectrum detected outside the cavitation chamber: ***a***, At different oil pressures; ***b***, At $P = 37$ atm in the presence of copper powder on the outer surface of the chamber. N_x is the total number of X-ray quanta detected for 5 min.

spindle oil were performed at different pressures (from 1 to 100 atm).

A detailed study of the effects that accompany cavitation has shown[6] that intense X-rays are detected using X-123 X-ray amplitude detector outside the thick wall of the working chamber at a certain critical regime of the liquid flow. The X-ray generation was synchronized with the stage of formation of microscopic cavitation bubbles (at pressures from 20 to 60 atm). Figure 2 *a* presents X-ray spectrum at different pressures. The spectrum was observed with the detector placed near the working chamber surface. Clearly, a pressure increase yields an increase in radiation frequency from 0.7 to 1.2 keV accompanied by a considerable decrease in intensity. With a further increase in the liquid pressure, the signal at the X-ray detector disappeared.

To study this anomalous phenomenon, the outer chamber surface (its flat part) was coated by standard (medical) gel for ultrasound with a fine copper powder (size of particles: 10–100 mkm). The fine copper powder is seen to result in the emergence of additional, harder radiation lines with energy of about 3.7–4 keV in the maximum (Figure 2 *b*).

We suggest that the generation of X-rays is caused by the action of acoustic shock waves on the surface atoms of the cavitation chamber[6,7]. The excitation of atoms and the subsequent X-ray generation occur under the pulse action of shock waves (acceleration, deceleration or deformation) on the atoms located on the outer wall of the cavitation chamber or acoustically coupled with the outer chamber surface[6,7]. The shock waves are formed on the inner surface of the chamber due to the collapse of bubbles in the liquid running under pressure through the channel to the chamber. In this case, the chamber surface is the X-ray source. These acoustic pulses were detected by flat piezoelectric gauge with a diameter of 20 mm. Formation of a periodic sequence of acoustic pulses on the outer surface is the result of positive acoustic feedback action along the cavitation chamber walls and modulation of both orifice hole parameters and precondition of bubble cavitation (Figure 1). In such the system, the process of transformation of chaotic sequence of weak shock waves (at lack of feedback) to the ordered sequence of intensive shock waves takes place. The period of the sequence (repetition frequency $\omega \approx 22$ kHz) is determined by feedback parameters. This system is 'bubble' analogous (cavitation bubbles instead of electrons) of the well-known radio-frequency Van-der-Pol generator with feedback[11].

Investigation of abnormal X-rays at cavitation of free water stream

The main part of the investigation of radiation processes at cavitation in the high-speed water jet was carried out using a KMT water jet system[7] intended for hydrodynamic industrial processing of various materials, including cutting. This system can form a high-speed water jet, the parameters of which are determined by the pressure range 250–2000 atm. The process of cavitation reaches its maximum at the end of the narrow channel inside a steel rod and near it in free space (in air).

Study of X-ray emission of the fast water jet emitted from the narrow channel

In the study of the emission spectrum of the water jet, a beryllium entrance window of the detector was located at a minimum accessible distance (of about 5 mm) from the jet and at a distance of 2–4 cm from the channel outlet in the steel rod. It was found that the water jet issuing from the channel to the air generates X-rays, the spectral maximum of which corresponds to energy of $E_x \approx$ 0.9 keV at a pressure of 600 atm (Figure 3, water). The free path length of this radiation in air does not exceed ≈ 6–7 mm. At a trial increase in the water pressure to 1000 atm, this maximum shifted from 0.9 to 1.1 keV.

Further studies were carried out on the radiation spectrum from the outer surface of the steel rod, which comprises an expanding channel with a cavitating water jet. It was found that the outer surface of the metal (steel) wall of the rod with a cylindrical inner channel generates X-rays with a peak at $E_x \approx$ 1.7–1.8 keV under the same pressure of 600 atm (Figure 3, Fe). When a continuous layer of fine lead powder is deposited on the rod surface and a reliable acoustic contact between the powder and the surface is provided by standard (medical) gel for ultrasound, maximum radiation energy shifts to the region of $E_x \approx$ 4.8–5.0 keV (Figure 3, Pb).

To increase the reliability of the recording process and study the spatial distribution of X-rays, test studies were performed using X-ray films.

First, a test study was carried out on the radiation that occurs in the immediate vicinity of the liquid jet surface and the output channel. For this purpose, two sheets of film were placed in a common package of light protective black paper. A package with a stack of films positioned without gaps was rolled in the form of a cylindrical surface with a radius of $R \approx 3$ cm and was fitted over the entire length of the rod. With this arrangement of the parts, the distance from the outer surface of the rod to the film is $\Delta R_1 \approx 2.3$ cm and that from the centre of the water jet is $\Delta R_2 \approx 3$ cm. Figure 4 shows the view of the two coaxial films after 15 min exposure at water pressure $P = 600$ atm. It is seen that, in the area located near the rod surface (upper portions of the images), there were intense X-rays. General regularities in the spatial distribution of this radiation are identical on both films. The radiation energy can be clearly estimated by comparing the weaker darkening of the second film (relative to the first film), which is associated with the radiation absorption in the volume of the first film.

Estimates based on the analysis of X-ray absorption in the bulk of a 0.15 mm thick film show that the radiation energy corresponds to about 2 keV, which is consistent with the spectrometer data shown in Figure 3. The lower portions of both films were almost pure, which is easily explained since the path length ≈ 6–7 mm of softer radiation with energies of about 1 keV from a cavitating water jet is much smaller than the distance from the jet to films $\Delta R_2 \approx 3$ cm.

Study of interaction of cavitation-induced X-rays with distant thick screen

The interaction of cavitation-induced X-rays with distant thick screen was studied[8]. To fix films and a screen, a

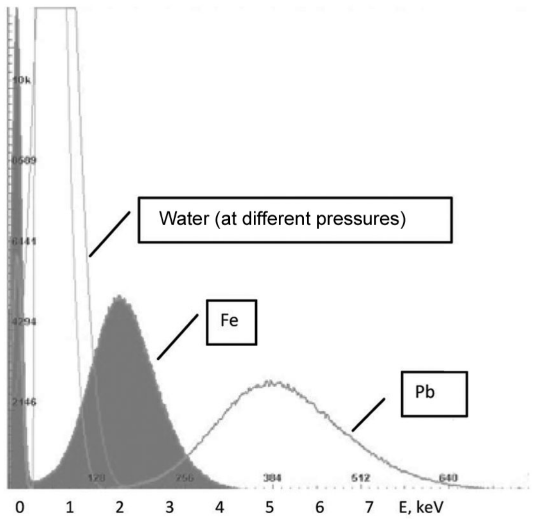

Figure 3. Spectra of X-radiation from different surfaces at cavitation of fast water jet at 600 atm.

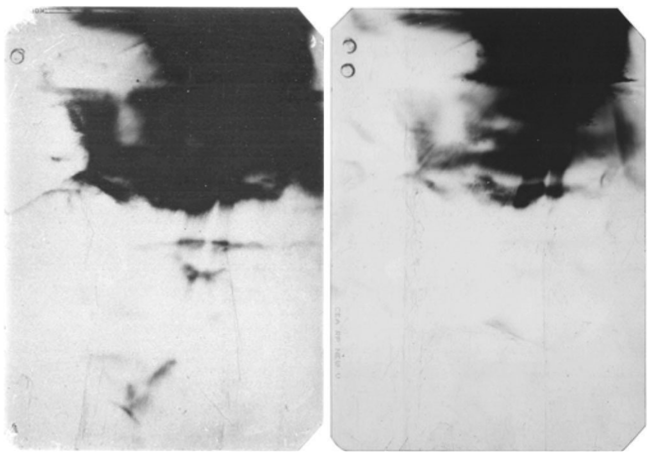

Figure 4. Images on X-ray films stacked tightly upon each other, rolled into a cylinder coaxially with the rod, and mounted so as to overlap vertically the widest part of the rod (upper dark part of the film) and the region near the channel outlet: (left) film is closer to the rod; (right) film is behind (without a gap) the first film.

plate from rigid foam was used. In the centre of the plate there was a hole 2.5 cm in diameter for the passage of the water jet or the placement of a rod 1.5 cm in diameter with an inner channel, and four parallel slots were at distances $L_1 = 3$ cm, $L_2 = 4$ cm and $L_3 = -3$ cm, $L_4 = -4$ cm from the hole centre at opposite sides of the hole.

In one of the nearest slots (at L_1), a thick screen 1 (3 mm thick steel plate with size corresponding to the X-ray film) was mounted vertically. Slot 2 (behind the steel plate) held two X-ray films placed in light protective black paper envelope of oriented similar to the steel plate. Two other pairs of films in similar envelopes were installed into slots 3 and 4 (at L_3 and L_4).

Figure 5 presents the results of an exposure of light protective paper envelope with pairs of films when the system was operating at a water pressure of 600 atm for 30 min and when the rod was placed between the vertically mounted films. These results turned out to be extremely paradoxical.

From Figure 5 it follows that the images on both films were in the form of separated localized spots, the position and configuration of which were completely identical. In addition, at the bottom of the figure, there is a dark band, the position and width of which correspond to the sizes of the slots in the plastic foam. The difference in the brightness of detected radiation on the first and second (rear) films relates to the radiation absorption in the first film.

The estimation of absorption similar to that carried out in the analysis of Figure 4 shows that the films were

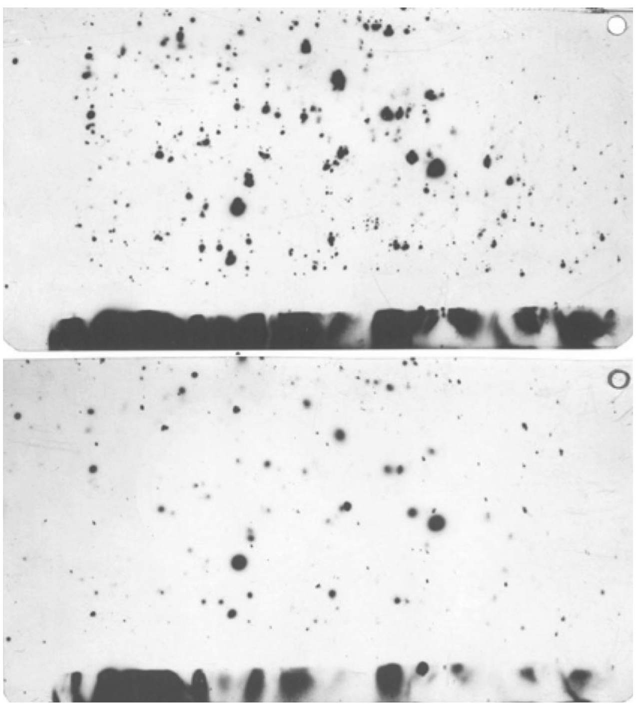

Figure 5. Images on plane X-ray (two films stacked tightly in a light protective paper envelope and mounted behind the steel screen). The appear film is closer to the screen.

irradiated with sufficiently intense X-rays with energies of about 2 keV. This is consistent with the parameters of radiation detected near the surface of a steel rod of similar material for shock effects accompanying cavitation. On the other hand, this radiation could in no way reach the films from the rod since the films were behind a thick screen. Moreover, they were installed at a relatively large distance from the rod surface (about 3.2 cm). This result is confirmed by the fact that there are no spots on the films at the location of the hole in the screen. Curiously, the other four films at opposite side of the rod surface at the same distances $L_{3,4}$ but not shielded by a thick steel plate, were completely clean.

Based on this comparison of the facts, it is clear that the source of the recorded low-diverging X-rays with the spatial distribution in the form of small-sized discrete spots is the thick screen.

One can make a reasonable assumption that, under the action of a field disturbance that affects the screen from the rod that is at a distance of 2.2 cm, radiation with energies around 2 keV is generated on the back portion of the screen (with respect to the cavitation source). If this field disturbance is coherent, then the secondary X-rays may also be coherent. The most likely contender for such a disturbance is the sequence of airborne acoustic shock waves generated by the rod. Each of these waves being incident on a closely located screen excites a coherent secondary shock wave in the bulk of the screen. These secondary waves pass the screen volume and, being reflected off the back portion, excite the atoms on it. Surface-distributed disturbances from each of the waves are mutually coherent and phased by the action of the shock wave. Spontaneous emission of these mutually phased sources results in the generation of X-radiation that is characterized by a large transverse coherence. If the front and rear surfaces of the screen are parallel, then upon the incidence of a plane shock wave, the generated X-rays will also be quasi-plane (except for very weak edge effects associated with diffraction). If the initial shock wave has a spherical or cylindrical shape, which reflects the geometry of the specific source of the shock wave, the X-rays will also be close to these shapes. In this interpretation, the presence of black bands in the lower portions of both films (Figure 5) becomes clear. Their appearance is associated with the lower part of the screen surface being cleared of paint and shaped as a small-angled wedge. This was done for a more secure screen attachment by the narrow slit in the plastic foam. Within this region, secondary soft radiation was emitted freely from the metal surface, which led to subsequent darkening of the films. Such a model is realistic and does not contradict the fundamentals of X-ray optics[7]. These results are similar to those of external X-rays generated on the outer surface of a closed chamber at glow discharge or electrolysis in numerous LENR experiments.

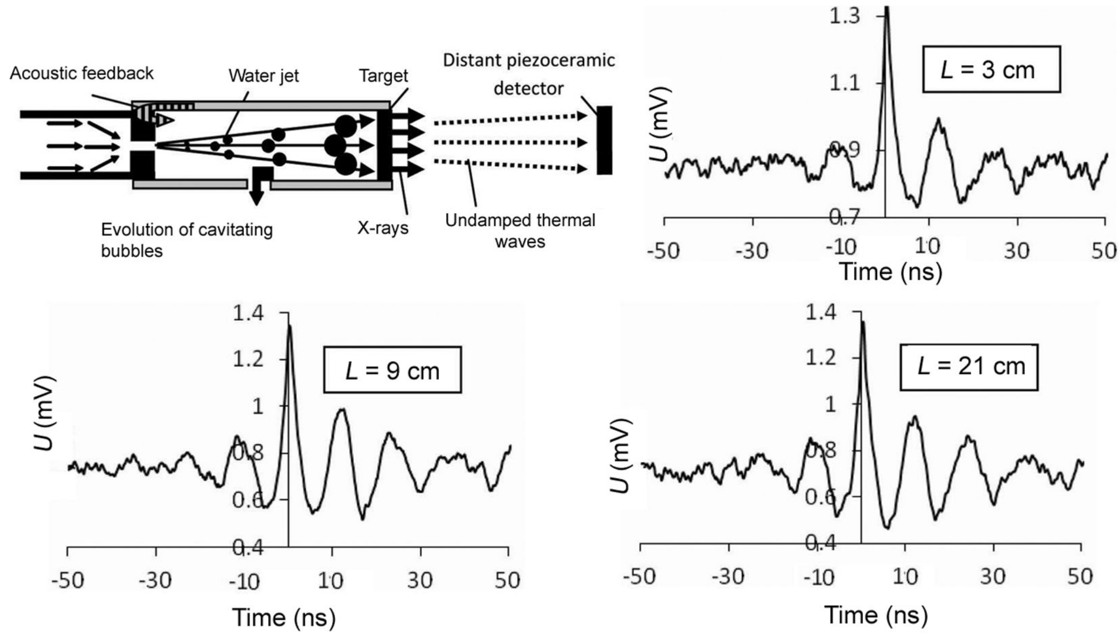

Figure 6. Experimental set-up for study of X-rays and undamped thermal waves at cavitation of fast water jet and high-frequency signals registered in air at different distances L.

Observation and investigation of undamped thermal waves in air at cavitation

During water cavitation simultaneously with the registration of X-rays we have registered previously unknown undamped thermal waves in air. Figure 6 shows the experimental set-up and the view of signals registered in air by broadband acoustic piezoceramic detector at different distances L from the outer surface of the target made of tungsten[9,10]. Registration of the acoustic signal with a frequency of $\omega_{\mathrm{HF}} \approx$ 80–85 MHz at distances L = 3–20 cm from the back portion of the target is the paradox that cannot be explained by 'standard' acoustics. The 'standard' formula for absorption of ultrasound has shown that at such a frequency the coefficient of absorption in air $\delta \geq 10^4$ cm^{-1} is very large, and the mean free path $\overline{l} \leq$ 1–2 μm is very small (10^5 times less L). This paradox can be resolved if we assume that it is not an 'usual' acoustic wave, but undamped thermal wave[9,10].

Existence of undamped temperature waves that can propagate without dissipation in environments with small time τ of local temperature relaxation has been theoretically predicted[8–10]. Such waves have a characteristic eigen frequency $\omega \approx \pi/2\tau$ and can be excited in environment under the influence of short heat pulses with duration $\Delta t < \tau$. Solution of heat transfer equation with delay (in the presence of finite time τ of local thermodynamic relaxation)

$$\frac{\partial T(x, t+\tau)}{\partial t} = G\frac{\partial^2 T(x,t)}{\partial x^2}, \tag{1}$$

is superposition of colliding thermal waves[8–10]:

$$T(\omega, x, t) = A_\omega \exp\left(-\kappa \frac{\cos\omega\tau}{\sqrt{1+\sin\omega\tau}} x\right)$$

$$\times \exp\{i(\omega t - \kappa\sqrt{1+\sin\omega\tau}\, x)\}$$

$$+B_\omega \exp\left(\kappa \frac{\cos\omega\tau}{\sqrt{1+\sin\omega\tau}} x\right)$$

$$\times \exp\{i(\omega t + \kappa\sqrt{1+\sin\omega\tau}\, x)\},\ \cos\omega\tau \geq 0, \tag{2}$$

fundamentally different from the solution of 'standard' heat equation without this delay

$$T(\omega, x, t) = A_\omega \exp(-\kappa x)\exp\{i(\omega t - \kappa x)\}$$

$$+B_\omega \exp(\kappa x)\exp\{i(\omega t + \kappa x)\}, \tag{3}$$

which determines the thermal waves with very strong damping $\delta \equiv \kappa = \sqrt{\omega/2G}$. For a system with relaxation, the damping coefficient and phase velocities of colliding waves

$$\delta = \kappa\cos\omega\tau/\sqrt{1+\sin\omega\tau}\ ,\ v_{\mathrm{p}} = \pm\sqrt{2G\omega/1+\sin\omega\tau}. \tag{4}$$

depend on the thermal diffusivity G, time delay τ and frequency ω of the wave. The source of such thermal waves is very short acoustic shock wave excited by cavitation on the inner (left) surface of the target (Figure 6). Reflection of this shock wave from the outer (right) surface forms the short thermal pulse with duration $\Delta t < 10$ ns in air. The parameters of this pulse satisfy the condition $\Delta t < \tau$ that leads to the generation of undamped temperature wave in air. The physical reasons of generation and propagation of these waves have been studied in detail[8–10]. This theoretical analysis correlates well with experiments[10].

Conclusion

The experimental results and conclusions that follow from the theoretical analysis show that intense acoustic shock waves associated with cavitation processes are a source of intense X-ray emission outside the cavitation region and working chamber. These experiments were repeated many times with different cavitation chambers. Every time we have observed identical effects – generation of controlled, directed X-rays. It is important to note that X-ray generation is not connected with a specific temperature of compressed microbubbles, but is the result of interaction of shock waves on the outer surface of working chamber. The similar mechanism of X-ray generation takes place at interaction with the outer surface of the shock waves generated by another processes (e.g. cracking of metal hydrides during hydrogen loading in LENR experiments).

Another important result of this study is connected with the detection and investigation of undamped high-frequency thermal waves. The frequencies (energies) of these waves depend on the properties of the medium in which these waves propagate. These frequencies are determined by the time τ of local thermal relaxation. In metals and semiconductors the value of τ is very small and appropriate frequencies lie in the IR and visible regions and can be excited only by ultrashort thermal pulses[9]. Similar but slightly lower frequencies correspond to low-temperature dense plasma[9]. For air the relaxation time depends on the pressure and temperature and is about $\tau \approx 5$–10 ns.

The results presented here indicate that undamped temperature waves can be generated during special conditions in air and may play a important role in heat exchange.

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