FIFTH INTERNATIONAL CONGRESS ON SOUND AND VIBRATION
DECEMBER 15-18, 1997
ADELAIDE, SOUTH AUSTRALIA

Experimental investigation of the influence of magnetic field on the cavitation inception in pulse rarefaction waves in water.

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Abstract

The influence of magnetic field on the cavitation processes in pulse rarefaction waves in water is investigated experimentally. It is shown, that water is transformed into a new state. This state is characterized by a temporary increasing of cavitation inception threshold and the significant influence of magnetic field on bubbly cluster dynamics. The life time of new state of water is found to depend on the intensity of loading. The mechanism of the influence of a magnetic field on the cavitation ability of water is proposed. It is based on the change of physical properties of cavitation nuclei under pulse loading at magnetic field presence. The possible influence of hysteresis properties of water [1] is excluded by preliminary loading the water samples with the chosen amplitude shock wave. A rarefaction wave is produced by reflecting a plane short (a few microseconds) shock wave from the free surface of water [2]. For the detection of the threshold of cavitation inception and dynamics of bubbly cluster the variable capacitance transducer method [2] is used.

Introduction.

Cavitation in liquids is one of the phenomena having statistical nature, and it is difficult to be quantitatively measured. A disperse of cavitational thresholds measured by acoustical or visual methods can achieve 20% [3], that's why an investigation of external factors influence on cavitational processes, if they lead to changes of the same order, are practically excluded. The working out of a capacity transducer method of cavitation investigation became a significant breakthrough in this field [2]. For using of this method, the accuracy of reproduction of registered curves behavior for intensive cavitation development is not usually over then 5 – 10%. The characteristics of this measuring system allow to detect reliably 10–15% changing of cavitational media characteristics under action of external factors. This article deals with the search of such external factors and possible methods of cavitational processes control.

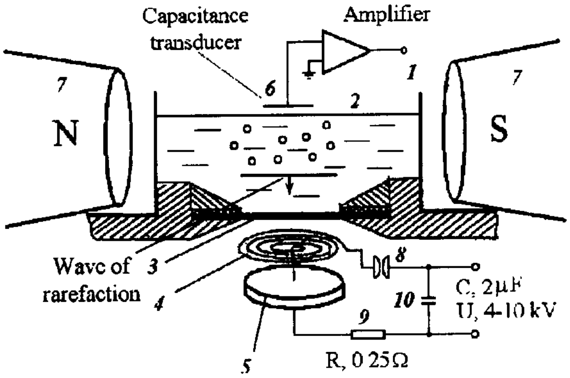

Figure 1: Experimental set–up.

Experimental set-up and scheme of experiments.

The block-scheme of electromagnetic shock waves generator and the experimental scheme are presented on Fig. 1. 1 is the tube with diameter 58mm made of lavsan film , 2 is the free surface of water, 3 is the membrane made of duralumin with thickness 0.6mm, squeezed on the contour with diameter 30mm, 4 is the Archimede spiral coil with diameter 30mm, 5 is the support disk of cuprous with thickness 2 mm, 6 is the capacitance transducer, 7 - is the constant magnet with induction B = 0,18T, 8 is the controlled spark gap 9 is the resistance R = 0,25 Ω, 10 – is the lowinductive battery of condensers $(2\mu F \times 10kV,\ L = 2,5 \times 10^{-8}G)$. A flat shock wave is created in filled up to level 30 mm with water tube 1 by pulse magnetic field pressure on conducting membrane 3 passing pressure impulse into liquid. A magnetic field appears as a result of discharge of low-inductive condensers battery 10 to flat coil 4 placed between shock membrane 3 and cuprous disk 5. Controlled spark gap 8 let us discharge the capacitors bank at range from 4,5 kV up to 10 kV. Resistance 9 provides the aperiodical mode of discharge and generation of single pressure impulse. Its amplitude is determined by a voltage magnitude on the condensers battery, thickness and material of membrane 3 and can be easily varied practically without impulse form changing from ten parts till hundreds atmospheres. A shock wave propagates as a flat disk with initial diameter approximately 25–30 mm toward the free surface of water 2. It transforms into rarefaction wave and propagates downward, initiating a growth of cavitational nuclei. Free surface displacement 2 is registered by capacity transducer 6. Transducer 6 is the cap made from brass with aluminized lavsan film with thickness 20 μm pulled on it.

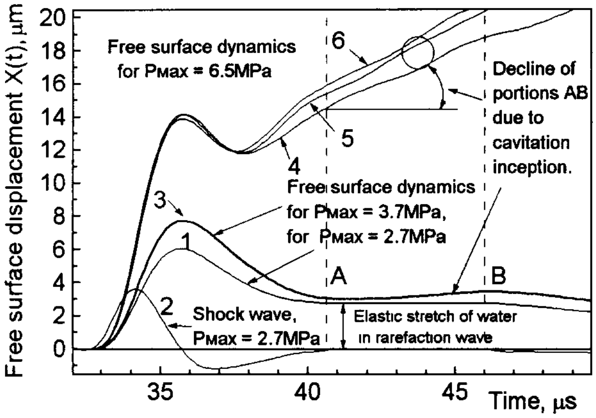

Figure 2.

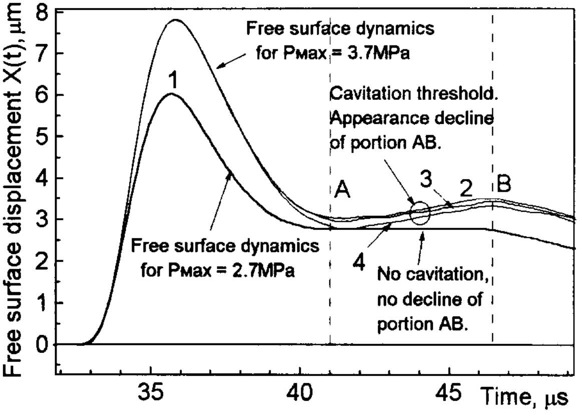

Figure 3.

The film is put into immediate contact with water and shift together with the free surface comparatively immobile central electrode with diameter $d = 15mm$, causing change of capacity and corresponding to it changing of voltage on the transducer. Transducer works in regime $Q = const$, doesn't need calibration and allows to obtain the time dependence of the absolute magnitude of free surface displacement $X(t)$ for the different intensity of loading (Fig. 2, 1).

Curve 1 show the free surface dynamics during the process of reflection of the shock wave (2.7MPa, Fig. 2, curve -2) without following cavitation inception.

Curve 3 show the free surface dynamics during the reflection of the shock wave with amplitude of cavitation inception threshold (3.7Mpa).

Curve 4–6 show the free surface dynamics under conditions of intensive cavitation processes and give a notion about average statistic disperse of curves from one series of the experiments for the constant intensity of loading (6.5MPa).

Under conditions of absence of cavitation phenomena, differentiating the plot of free surface displacement $X(t)$, we determine its velocity $V_{FS} = dX(t)/dt$ which in the framework of acoustic approximation is equal to the doubled liquid mass velocity $u(t)$ in shock wave:

$$V_{FS} = 2 \cdot u(t) \tag{1}$$

and uniquely corresponds with pressure

$$P(t) = \rho \cdot c \cdot u(t) \tag{2}$$

(Fig. 2–2) Here ρ is the density of water, c is the speed of sound in it. Equation (2) is used to determine the amplitude of pressure in shock wave. The equation (1) became invalid on the boundary A (Fig. 2, dash line) when the process of shock wave reflection is finishing, and a lifting of free surface relatively an initial level is determined by spring stretching of water sample in the field of rarefaction wave propagating down. Boundary B corresponds to the arrival moment of side discharge from the walls of tube 1 to the central electrode of capacitor transducer 6.

When cavitation appears, a free surface prolongs its motion even after the shock wave reflection being over (Fig. 2,3-6), tracing an increasing of total volume of bubbles arising during the process of rarefaction wave penetration in deep water sample. The declining of AB portion with linear dependence of free surface displacement on time (Fig. 2,3–6) characterizes an intensity of inertial cavitation development. So, in time dt a rarefaction wave displaces down at distance $c \cdot dt$, activates n cavitation nucleus per liquid volume unit and causes their growth till intermediate size r. Designate an area of rarefaction wave section as S, the whole number N of bubbles arisen in it during the time dt we'll write as (3)

$$N = n \cdot S \cdot c \cdot dt, \tag{3}$$

the overall volume of them

$$dV = N \cdot V_{bubble} \tag{4}$$

there

$$V_{bubble} = 4 \cdot \pi \cdot r^3/3, \qquad (5).$$

From the other hand, a liquid volume change will lead to a surface lifting for a magnitude of dh, because the wave is flat and the sample are deformed with respect to one coordinate. The volume in crease

$$dV = dh \cdot S. \tag{6}$$

Comparing (3), (4) and (5), we get

$$n \cdot c \cdot dt \cdot V_{bubble} = dh. \tag{7}$$

here the magnitude

$$\alpha = n \cdot V_{bubble} \tag{8}$$

is the parameter of vapor-gas or hollowness medium contents, and the relationship $dh/dt = V_{FS}$ is the free surface velocity. Comparing 6, 7 and 8, we obtain

$$V_{FS}/c = \alpha \tag{9}$$

Hence, immediately after reflection of the shock wave from the free surface of water, the relationship of free surface velocity (the declining of AB portion, Fig. 2, 3) to speed of sound gives the magnitude of gas contents α which is the relation ship of whole volume of cavitation bubbles to liquid volume in a developing cavitation cluster. The obtained expression (9) was checked experimentally and used for the developing method of cavitation processes investigation in opaque to light suspensions [4]. A knowledge of magnitude α allows to determine a specific energy expended ρ_E for bubbles formation per unit of medium volume

$$\rho_E = P_0 \cdot \alpha, \tag{10}$$

where $P_0 = 101325\ Pa$ is atmospheric pressure.

According to (10), the equal declining of curves 4–6(Fig.2) on the AB portion testified that every time for fixed level of loading the equal energy is stored by bubbles. It means that bubbles concentration is also constant, because its average size is determined by the duration and amplitude of rarefaction wave which are stable. Hence the even small declining from the showed on Fig.2 (4–6) normal run of the process should be determined by an external factors influence. In the present article a current magnetic field with inductance $B \approx 0.18T$ is chosen as such an influence factor. Current magnet 7 (Fig.1) is mechanically isolated from the tube 1 and registration system 6. It can be displaced 200mm from the tube, when the magnetic field induction in it is less then 0.005T.

Experimental results.

The experiments were held with distilled water samples settled during 1–2 weeks. To exclude the hysteresis effects influence [1] on the measuring results, an investigated sample was previously loaded few times by given pressure impulse, and all the further measuring were taken with interval 1–2 min for the same load intensity.

The results of experiment investigation of magnetic field influence on cavitation threshold for a water sample never undergone to intensive loading before are showed on Fig. 3.

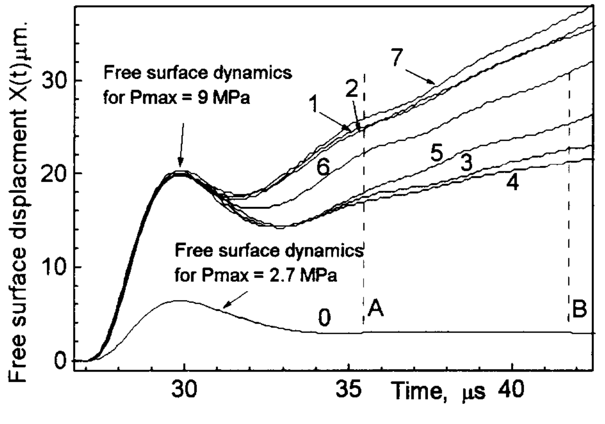

Figure 4.

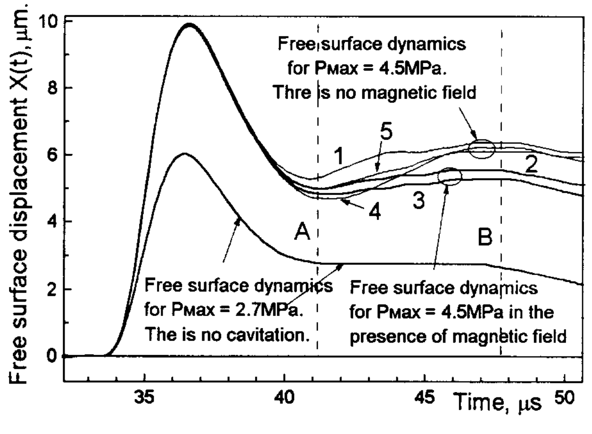

Figure 5.

Curve 1 shows the free surface dynamics during the reflection of the shock wave with amplitude 2.7 MPa “pre-threshold” mode of loading (horizontal portion AB). Curves 2–4 demonstrate the threshold (for the described load conditions) of free water surface dynamics (appearance decline of portion AB) due to reflection of shock wave with amplitude 3.7 MPa as for magnetic field presence (curve 3), as for its absence (curve 2 is before switching on the field, curve 4 is after its switching off).

The analysis of the presented plots allows to conclude, that in the framework of the used method accuracy, a direct influence of magnetic field of the mentioned intensity $0.18T$ on a cavitation threshold of water and consequently on physical properties and structure of cavitation nuclei is absent. Only the further increasing of shock wave amplitude till 9 MPa allowes to display trustworthy magnetic field influence on dynamics of cavitation processes in water. The results of the experiments are presented on Fig. 4.

Curves 1 show the free surface dynamics without magnetic field. Curve 2 is wrote down for the first loading at the magnetic field presence. It is seen considerable declines don't happen. However water reacts with nearly two time less free surface lifting upon the repeated loading by an identical pressure impulse at a magnetic field presence Fig. 4 (curve 3–4). The 10 minutes pause doesn't lead to considerable changes Fig. 4 (curve 5). Hence the new water state at the magnetic field presence remains more then 10 minutes. The taking off the field leads to some changes during the first loading after that (Fig. 4,curve 6), and only the second loading without magnetic field leads to water return to an initial state. It is easy to be convinced of it by comparing curves 1,2 and curve 7. Curve 0 corresponds the ”pre-threshold” mode of loading. Hence it is possible to conclude that the sufficiently intensive process of cavitation at magnetic field presence leads to water transition into the state characterized by more ability to resist to cavitational distraction. Life time of such a state may excel 10 minutes but effect decreases gradually. The decline increasing curve 5 (Fig.4) points out to it.

The samples of water loading with the shock wave of intermediate between 4 MPa and 9 MPa amplitude also leads to the changes of its state but the effect is unstable and after 3–5 minutes water may return to initial state even with magnetic field presence. The influence of magnetic field on the value of the threshold of cavitation inception can be observed in water after putting it into activated state by means preliminary loading by the 9 MPa shock wave. In this case an existence or absence of it only is traced (Fig. 5, curve 1,2,5 without field; curve 3,4 with field). The post–loading increasing cavitation threshold value effect don't have any connection to magnetic field and was discussed in [1].

Discussion

Using the data of picture 4, we can make some numerical estimations which may reveal the essence of this problem and help us to make some conclusions:

1. From the slope of curve 1 at portion AB we can get velocity of the free surface $V_{FS} \approx 1.8\ m/s$, then from (9) the value of $\alpha \approx 1.2 \cdot 10^{-3}$ and from the (10) we determine the density of potential energy $\rho_E \approx 120\ J/m^3$ of bubbles per unit of volume which was taken from the rarefaction wave respectively.

2. The maximal shock and rarefaction wave energy density can be estimated as $\rho_{SHW} = \frac{P_{MAX}^2}{2\cdot\rho\cdot c^2} \approx 1.8 \cdot 10^4\ J/m^3$. It means that at distances about 10–30 mm we can neglect the cavitation energy losses ($\rho_E << \rho_{SHW}$).

3. Curve 1 (no magnetic field) and curve 2 (first time after switching on magnetic field) practically go one along another. It is one more proof of our conclusion about absence of direct influence of magnetic field presence on the cavitation properties of water.

4. For the third and the fourth loading at magnetic field presence we have $V_{FS} \approx 0,9\ m/s$, $\alpha_B \approx 6 \cdot 10^{-4}$ and $\rho_{EB} \approx 60\ J/m^3$. Comparing with the first case, we have general energy losses

$\rho_{BQ} = \rho_E - \rho_{EB} \approx 60\ J/m^3$.

5. Curve 5 shows that in this particular case the time of new water state existence can excel 10 minutes.

6. The magnetic field switching off does not immediately lead to the recovering the initial properties of water (Fig.4, curve 6). In this case $V_{FS} \approx 1,5\ m/s, \alpha \approx 10^{-3}$, potential energy of bubbles $\rho_{EQ} \approx 100\ J/m^3$ and still there are energy losses about $\rho_Q = \rho_E - \rho_{EQ} \approx 20\ J/m^3$.

7. Only the second loading may lead to the complete restoration of initial properties of water sample (Fig.4, curve 7).

Compare items 4 and 6 we can make a conclusion, that there are two different mechanisms which lead to energy losses. From the analysis of item 6 we can see that the energy losses $\rho_Q \approx 20\ J/m^3$ have not any connection to magnetic field. Taking into account the data of items 4 and 6 we may determine the energy losses due to interaction with magnetic field: $\rho_B = \rho_{BQ} - \rho_Q \approx 40\ J/m^3$.

As a matter of fact, pressure is the energy density, so for the crude estimation we can consider action of external forces as an action of equivalent pressures $P_B \sim \rho_B$ and $P_Q \sim \rho_Q$. The intensity of loading is constant, so we can make an assumption that in all the described cases the energy losses ρ_E and respectively potential energy of cavitation bubbles are constant and the final size of bubbles is determined by the value of additional pressure P_B and P_Q with acting during the bubbles growing up. We may determine their value from the following equations: $P_0 \cdot \alpha = \rho_E$ (1-st item); $(P_0 + P_B + P_Q) \cdot \alpha_B = \rho_E$ (4-th item); $(P_0 + P_Q) \cdot \alpha_Q = \rho_E$ (6-th item). So we have $P_B \approx 0.8 \cdot P_0$ and $P_Q \approx 0.2 \cdot P_0$. It is necessary to understand the nature of this pressures.

Water is diamagnetic and its magnetic interaction with magnetic field can be neglected. Immediately comes an idea about charge appearing on the bubble internal surface and in vicinity of it. It is let us propose some explanation of the observed phenomenon. Water-gas boundary layer became an ionic surface conductor and if it is good enough we will see reaction from the field, which can be presented as a pressure of magnetic field $P_F = B^2/2\mu$ and so-called Maxwell tensions $P_M = B^2/\mu$, there μ is magnetic constant [6]. General pressure will have value $P_FM = P_F + P_M \approx 0.4\ P_0$ which is just half of our estimation of P_B. This assumption can be valid only if the thickness of the skin layer is less, then the radius of the bubble (it's thickness of water layer involved in the motion by bubble). From the well-known expression for the skin effect $\delta = 2 \cdot (2\mu \cdot \sigma \cdot \omega)^{-1/2}$ where $\omega = 2\pi/\tau$ and τ–duaration or rarefaction wave, under conditions $\delta \approx r$ we determine that σ must be more then $2 \cdot 10^7\ (\Omega \cdot m)^{-1}$, which is extremely high value. For comparison σ for copper is $6 \cdot 10^7 (\Omega \cdot m)^{-1}$.

There is an another possibility of magnetic field interaction with conductive media. It is specific force of magnetic viscosity $f \approx \sigma \cdot B^2 \cdot U$ which can be responsible for the another half of P_B value. Here $U \approx r/\tau$ is averige velocity of the bubble wall, which maximum radius $r \approx 0.2mm$ (Fig. 6), σ – specific conductance of medium. If the magnetic viscosity force f provides the additional pressure $P_V = 0.4 \cdot P_0 \approx f \cdot r$, then the value of σ must excel $8 \cdot 10^7 (\Omega \cdot m)^{-1}$.

The last possibility of media interaction with magnetic field is the Joul's losses of energy [6] which we can estimate from expression $Q \approx \frac{j^2}{\sigma} \cdot \tau$, where $j = \sigma \cdot U \cdot H$ if $U \perp H$ then $Q = \sigma \cdot U^2 \cdot H^2 \cdot \tau$. If $Q = \rho_B \approx 0.4\ P_0$ then $\sigma = \frac{Q}{v^2 \cdot H^2 \cdot \tau} \approx 8 \cdot 10^7\ (\Omega \cdot m)^{-1}$. It's the same as for magnetic viscousity order of magnituade σ. which means that we face to the phenomenon when effective impulse conductivity of water under definite conditions may reach this value for copper. Usually conductivity of electrolytes ($\sigma = 1 - 10^3\ (\Omega \cdot m)^{-1}$) is determined by settled velocity of ions, which is about $10^{-4} - 10^{-5}\ m/s$ under normal conditions. But we have motion of ionized water layer in vicinity of the bubble wall, whose velocity is about $100\ m/s$. So the velocity of water mixing may be of the same order and conductivity increase seems to be reasonable.

However, for a charge appearance it is necessary to create conditions for gas or water molecules ionization and dissociation. From this point of view let us analyse the investigated process of shock wave reflecting from a free surface. Going through a water sample to a free surface, such a shock wave activates cavitation nuclei [1] and coming back being inverted, initialize a further growth of them up to $r \approx 0.2mm$ and accelerates the process of collapse till supersonic velocities with the further shock waves generation (Fig. 6) which can be the necessary condition of the analyzed effects revealing.

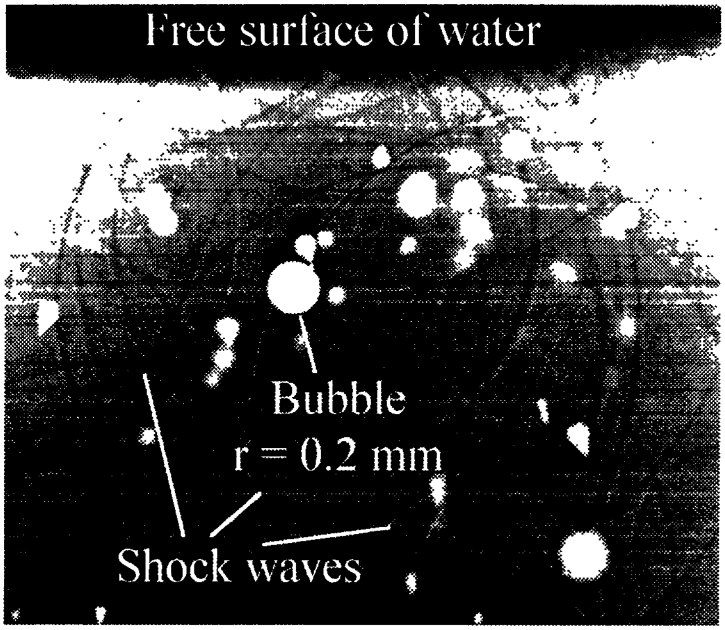

Figure 6.

The additional acceleration happens due to turning negative pressure phase (Fig. 2) into positive impulse accelerating the collapse process. The shock wave generation might be sufficient condition for arising high temperature inside the bubble. But, according to the author opinion, there is no need for bubble contents hitting to the few thousand degrees and ionized molecules. Probably, in vicinity of the center of collapse forms the area of overheating liquid with high concentration of dissociated molecules of water (0.6 eV - energy of dissociation of water at 20^oC, 2.5–5 eV — ionization energy of gas molecules, which means that probability of dissociation is 65– 4200 times more), which has not time to cool down and recombinate. It evaporates with explosion in the cavern of expanding bubbles during its' grow-up phase following after collapse. The separation of ions is taking place just during this stage. According to the well-known expression for the Larmor's radius $R_L = \frac{m_I \cdot V_I}{e \cdot B}$, where m_I– mass of ion, e–its charge,V_I is root–mean–square heat velocity, we can get $R_{H^+} = 1.6 \cdot 10^{-4} m$ for the H^+ ion and $R_{OH^-} = 6.6 \cdot 10^{-4} m$ for the OH^- ion at 20^oC. For the successful separation this ions must deviate from the general direction of motion at least on a few diameters of molecules at a free path length L. If pressure is P_0, then $L \approx 10^{-7} m$ and deviation less then diameter of molecules. But pressure inside the expanding bubble is less than the water saturated vapour pressure for which $L \approx 4.4 \cdot 10^{-6} m$ and deviation is about $6 \cdot 10^{-8} m$. So the magnetic field is in a position to take over the function of their detachment.

Next question is a long life time of "activated" state. Adsorbed ions have a big linkage power (adsorption energy) with water surface (practically the ionization potential 4.6 eV for the OH^- and 12 eV for H^+) and turn to be fixed with the "place of landing". A direct calculation of characteristic time of its' diffusion to partners of the opposite charge according equation $t = t_0 \cdot exp(-E/kT)(t_0$ is the period of ions oscillations, E is the energy of adsorption) can achieve tens of yeas. But in water the main type of conductivity connected to the proton exchange mechanism with the energy $E \approx 1eV$, $t_0 \approx 7 \cdot 10^{-14}s$ and characteristic time t is about few hours. Hence the adsorbed by water ions can be close to each other, have the strong Coulomb interaction with molecules of water and between themselfes. They will have a long recombination time and hinder the free motion of water including its molecules in its hydrate cover which leads to the water viscosity increase. According to this assumption the additional energy losses (item 6) we can introduce as an additional pressure of viscous forces for the expanded sphere:$P_{VIS} = 4\eta \cdot U/r$. Ander condition that $P_{VIS} = P_Q$ we will get value $\eta \approx 0.013\frac{N}{m^2 \cdot s}$. It's surpasses ten times this value for water and corresponds to viscosity of 70% solution of H_2SO_4 in water. Obviously that viscosity and conductivity of water will depend on a distance from the surface of bubble with maximum on it.

It is necessary to point out that the presence of magnetic field may lead to an irregularity in ions distribution on the bubble wall and rise of local ununiform charged areas which can affect on bubbles dynamics.

Taking off the magnetic field, we exclude the influence on the dissociation and recombination process, eliminate the primal directions of motion and make an ions hitting on any part of surface of cavity equiprobable. It leads to ions majority recombination and recuperation properties of cavitation nuclei.

Conclusion.

According the presented results, there is a possibility to work out the process of water "activation", which leads to the improvement of cavitation water strength. It is necessary to point out, that the present work doesn't deal with the "magnetic water" problem, because, a direct magnetic field influence on water properties was not discovered. Here the necessary condition of the effect presence is the intensive bubble cavitation development in the magnetic field presence.

This work was supported by RFFI grant 96-02-19327.

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