ACTION OF ULTRASOUND ON THE RISE OF A LIQUID IN A CAPILLARY TUBE AND ITS DEPENDENCE ON THE PROPERTIES OF THE LIQUID

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The dependence of the ultrasonic capillary effect on the viscosity, vapor pressure, surface tension, and gas content of the liquid is investigated.

The action of ultrasound on the rise of a liquid in a capillary tube as a function of the properties of the liquid has scarcely been investigated. This problem is discussed only in [1], in which it is noted that surface-active substances and gas content affect the maximum height of water in a fine tube.

Considering the results of [2-6], in which it is shown that cavitation is a decisive factor in the ultrasonic capillary effect, it is expected that the action of ultrasound on the rise of a liquid in a capillary tube will depend on the properties of the liquid that in some measure influence the dynamics of cavitation bubbles, namely the vapor pressure P_V, the gas content α, the viscosity η, the surface tension σ, and the wettability of the tube material. It does not appear feasible, however, to determine experimentally the dependence of the effect on the stated properties in explicit form, because when any one of them is varied (with minor exception), the others change as well. Nonetheless the qualitative nature of the influence of the properties of the liquid (and in certain instances the quantitative aspect), as will be shown below, can be determined. To attain this goal in the present study we have used the arrangement shown schematically in Fig. 1.

The temperature of the liquid in the reactor vessel is maintained constant within ±0.5°C error limits and is monitored by the Chromel—Copel thermocouple 13, which is situated near the end of the capillary tube. Thermostatic control is realized by pumping oil through an internal coil; the thermocouple emf is measured and recorded with the potentiometer 12.

Forced mixing is realized by means of a vane rotated by the electric motor 5. Mixing is necessitated by the fact that the liquid heats up rapidly at high sound intensities and it is impossible to maintain a constant temperature by natural convection and acoustic streaming alone (particularly in working with high-viscosity liquids). The action of ultrasound on the liquid in the capillary tube is estimated according to the excess pressure ΔP_0 that must be maintained above the capillary meniscus in order to keep the meniscus at the height H_0 of the normal capillary effect.

The experiments are conducted in the following sequence. The capillary tube is lowered into the liquid vessel and is fixed at a prescribed point above the radiating transducer by means of a coordinate positioning mechanism. The valve 9 connects the capillary—manometer—compressor system with the atmosphere. After the liquid stops rising under the influence of the capillary forces, the valve is closed, and the oscillator 1 is turned on. Under the action of ultrasound the liquid tends to rise to a new height. It is then restored to its original position by using the pump 11 to increase the pressure above the meniscus. The pressure ΔP_0 is measured with the standard manometer 10. The experiments are conducted in a vessel deadened with sound-absorbing porous rubber, and the excited wave is close to a traveling wave. The level of the liquid above the radiator is equal to 3λ. The properties of the liquids are varied by different techniques. The fundamental results are given in Figs. 2-4.

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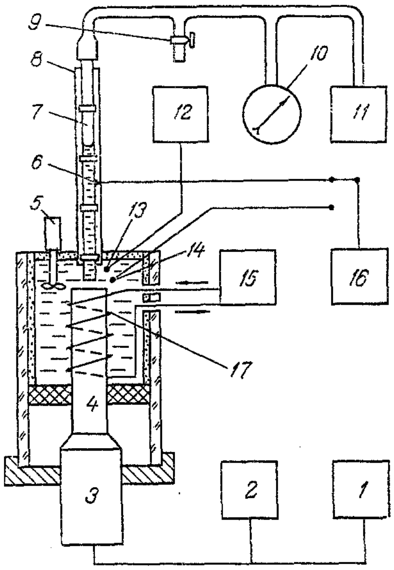

Fig. 1

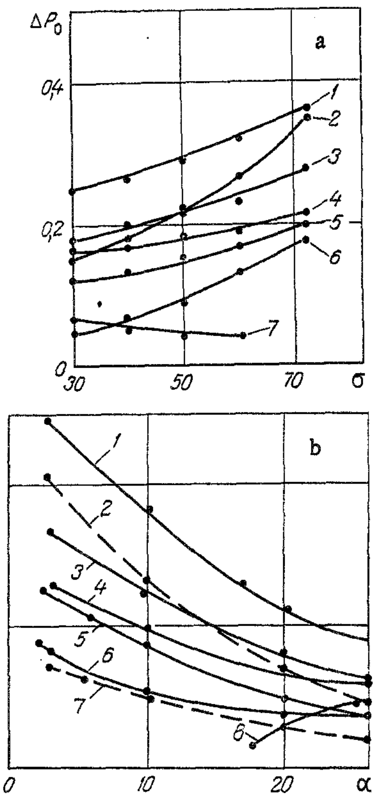

Fig. 2

Fig. 1. Schematic of the experimental arrangement. 1) UZDN-1 oscillator; 2) Ch3-34 frequency meter; 3) magnetostrictive transducer; 4) waveguide (diameter 15 mm); 5) electric motor; 6) piezoelectric receiving transducer; 7) capillary tube; 8) guide plate of coordinate positioning mechanism; 9) valve; 10) standard monometer; 11) pump; 12) ÉPP-09 potentiometer; 13) Chromel—Copel thermocouple; 14) spherical hydrophone; 15) thermostat; 16) S1-16 oscilloscope; 17) coil conduit.

Fig. 2. Pressure ΔP_0, 10^5 N/m^2, versus surface tension σ, dyn/cm (a), and gas content α, mm^3/cm^3 (b), at $t = 20°C$. a) $\alpha = 10$ mm^3/cm^3; $d = 0.11$ mm; $f = 21.7$ kHz (2, 3), 41.9 kHz (1, 4-7); $\delta = 4$ mm (1-3, 5-7), 0.05 mm (4); $A = 9.5$ μm(6), 4.5 (1, 4), 3.2 (5), 0.9 (7), 4 (3), 8 μm (2). b) $\delta = 4$ mm; $f = 21.7$ kHz (2, 7), 41.9 kHz (1, 3, 4-6, 8); $d = 0.11$ mm (1, 2, 8), 0.2 (3, 4), 0.48 mm (5, 6, 7); $A = 4.5$ μm (1, 4, 6), 12 (3, 5), 10.5 (2, 7), 0.9 μm (8).

I. Wettability and Surface Tension

1. The wetting angle characterizes the interaction of the liquid with the surface of the solid, and so it can be varied between rather wide limits (for example, by hydrophobization of the surface) without changing the other properties of the liquid. In this work we hydrophobize the capillary duct by the application of a dimethylchlorsilane $(CH_3)_2SiCl_2$ film, which is deposited by pumping a 10% solution of the compound in gasoline through the capillary tube with subsequent drying. After this treatment the surface of the duct becomes nonwettable, and the liquid does not rise in the tube, in fact it drops below the level in the reactor vessel. In a cavitating ultrasonic field, however, the liquid rises in both the wettable and the nonwettable tube, and the same excess pressure ΔP_0 is required in both cases to keep the meniscus in the original position. This result indicates that the ultrasonic capillary effect does not depend on the wettability of the working surface of the tube wall. We have thus corroborated the previous conclusion [5] that ultrasonic irradiation of the meniscus does not yield any significant contribution to the investigated effect.

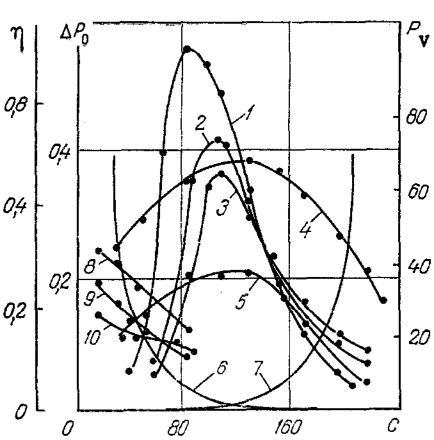

Fig. 3

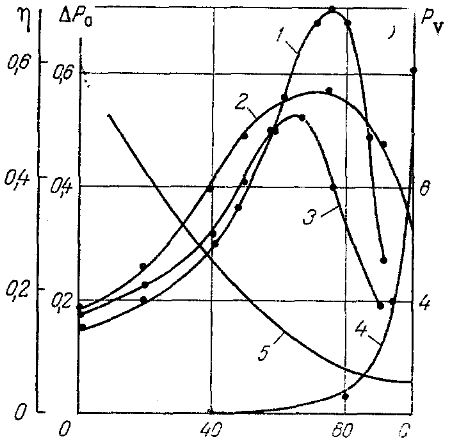

Fig. 4

Fig. 3. Pressure ΔP_0 (1-5), viscosity η, kg/m·sec (6), and vapor pressure P_V, mm Hg (7), versus temperature t in glycerin, and $\Delta P_0(t)$ in water (8-10), $f = 41.9$ kHz; $d = 0.2$ mm; $\delta = 4$ mm (1-3, 8, 9), 0.05 mm (4, 5, 10); $A = 9.5$ μm (2, 5, 9, 10), 4.5 μm (3, 8). Gas content of water and glycerin $\alpha \approx 8$ mm^3/cm^3 .

Fig. 4. Pressure ΔP_0 (1-3), viscosity η (4), and vapor pressure P_V (5) versus glycerin concentration C, %, in water—glycerin mixture, $t = 30$°C; $f = 41.9$ kHz; $d = 0.11$ mm; $\delta = 4$ mm (1, 3), 0.05 mm (2); $A = 9$ μm (1, 2), 4.5 μm (3).

If, on the other hand, the hydrophobizing film is deposited on the end of the tube, then for small ultrasonic amplitudes A at the radiator the pressure ΔP_0 increases 10-20% in comparison with the tube without the nonwettable film at the end. Moreover, when the tube with the nonwettable end is used, there is a slight decrease in the threshold amplitude at which a greater rise under the action of ultrasound is observed. The indicated changes can be attributed to the fact that the liquid is more easily detached from the nonwettable surface than from the wettable surface [7]. As a result, first of all, the cavitation threshold is lowered and, second, the number of cavitation nuclei increases, so that for small amplitudes the concentration of cavitation bubbles increases and the pressure ΔP_0 increases accordingly.

2. The surface tension is varied by the introduction of small additives of a surface-active substance, which in this case is acetic acid with a concentration of up to 5% in water. The other properties are practically unchanged in this case. It is apparent from Fig. 2a that the effect diminishes with a decrease in σ. With a decrease in the surface tension the energy and rate of collapse of the bubbles decrease [8]. As a result, the energy and velocity of the cumulative jets generated by this process decrease [9, 10], and the entrance of these jets into the capillary tube, according to [4-6], governs the action of ultrasound on the liquid therein. Consequently, from the point of view of the hypothesis developed in [4-6] the reduction of ΔP_0 with the addition of acetic acid to the water can be explained by the reduction in the rate of collapse of the cavitation bubbles. With a reduction in σ, in addition, the bubbles increase in size. This effect increases the screening action of the cavitation zone, whereupon the sound intensity at the end of the capillary tube decreases. The latter consideration takes on ever-increasing significance with distance from the radiator, because the effect diminishes more rapidly for small δ than for small values of the latter (Fig. 2a, curves 1 and 4).

II. Gas Content

The gas content is measured by a gas-chromatographic technique and is varied by degassing, settling, boiling, or ultrasonic irradiation. An increase in the gas content, of course, causes the number of nuclei to increase and the cavitation threshold to drop. Also, since cavitation is the decisive factor in raising the level of the liquid, it is the decrease in the cavitation threshold that accounts for the experimentally observed reduction in the threshold amplitude at which the effect sets in.

The increase in the pressure ΔP_0 with increasing gas content (Fig. 2b, curve 8) for small amplitudes ($A \lessapprox (2-3)A_{thr}$, where A_{thr} is the amplitude corresponding to the cavitation threshold) is probably attributable to an increase in the concentration of cavitation bubbles N. However, for large A, such that the cavitation zone is already well developed and N is close to saturation (i.e., varies only slightly), the pressure ΔP_0 decreases with increasing α, the influence of the gas content increasing with the amplitude at the radiator A, as witnessed by the increased steepness of the curves $\Delta P_0(\alpha)$ (Fig. 2b, curves 5 and 6). With an increase in α the pressure of the vapor—gas mixture in the bubble interiors increases. As a result, their energy and collapse rate decrease, causing a reduction in the energy of the generated cumulative liquid jets and a corresponding reduction in the value of ΔP_0.

The growth of the influence of α with distance from the radiator is caused by an increase in the energy losses in the cavitation zone. As a result, for large values of δ the effect diminishes not only due to the pressure reduction inside the bubbles, but also due to the reduction of the sound intensity at the end of the capillary tube.

III. Vapor Pressure

Increasing the vapor pressure P_v of the liquid should have the same effect as increasing the gas content. The value of P_v can be varied either by varying the temperature or by admixing various liquids.

As the temperature of the water is increased from 20 to 80°C its surface tension varies from 72.5 to 62.5 dyn/cm. Such a small change, according to the results of Sec. I, cannot alter ΔP_0 by more than 5-10%. The viscosity of the water decreases 50%, but the density ρ only decreases 1.5%. According to [8], the variation of ρ and η between such limits has scarcely any influence on the nature of the motion of the cavitation bubbles. The vapor pressure of the water in this case increases more than 20-fold. Consequently, the reduction of the pressure ΔP_0 in the water with increasing temperature (Fig. 3, curves 8-10) can be identified mainly with a variation of the vapor pressure, which, like an increase in α, increases the pressure p_{vg} of the vapor—gas mixture inside the bubbles and, hence, decreases their energy and rate of collapse. The influence of P_v grows stronger with increasing δ due to the absorption of acoustic energy, where the absorption increases more rapidly with δ as α is increased.

Viscosity. To investigate the influence of viscosity on the ultrasonic capillary effect we use mixtures of glycerin with water at various concentrations, as well as glycerin at various temperatures. The results are given in Fig. 3. The density and surface tension vary during mixing of the water and glycerin within limits that do not exert any appreciable influence on the cavitation bubble dynamics. According, the variation of the pressure ΔP_0 with C (Fig. 4) can be attributed to the variation of the viscosity η and vapor pressure P_v. The viscosity of the mixture as the glycerin concentration is varied from 0 to 100% ($t = 30$°C) varies from 0.008 to 0.62 kg/m·sec (Fig. 4), while the vapor pressure decreases from 19 to 1.2 mm Hg [11]. Thus, with an increase in C two factors affect the cavitation bubble dynamics: a decrease of the vapor pressure and an increase of the viscosity. In the expansion phase both of these factors promote an increase in the number and sizes of the bubbles. In the collapse phase, on the other hand, they exert competing effects; on the one hand, the increase in the viscosity with increasing glycerin concentration causes a reduction in the collapse rate due to increased friction and, on the other, the reduction of the vapor pressure promotes an increase in the collapse rate due to a decrease in the pressure of the vapor—gas mixture inside the bubbles. As C is varied from 0 to 75% the viscosity η increases only slightly, as seen in Fig. 4, while the vapor pressure decreases almost by an order of magnitude. In this interval of C, clearly, the variation of P_v is decisive, and the growth of ΔP_0 is attributable to precisely this factor. But if $75\% < C < 100\%$, the viscosity changes very slightly, while the vapor pressure changes considerably. It is evident from Fig. 4 that ΔP_0 decreases in this case, obviously because of a reduction of the bubble energy and collapse rate due to the increased pressure of the vapor—gas mixture inside the bubbles.

The curves $\Delta P_0(t)$ in glycerin (Fig. 3, curves 1-5), like the curves $\Delta P_0(C)$ discussed above, exhibit an extremal behavior. The maximum of the effect is attained at a temperature $t \approx 80$-90°C. In glycerin P_v and η vary with increasing t in approximately the same way as with increasing C in the glycerin—water mixture (Fig. 3, curves 6 and 7). Accordingly, the form of the curves $\Delta P_0(t)$ is similarly explained.

The curves $\Delta P_0(t)$ for glycerin with small values of δ (4, 5) have a gentler slope than for large values of δ (1-3). Also, with an increase in δ the maximum of the curves $\Delta P_0(t)$ shifts to the left toward smaller values of t. This behavior has two causes. On the one hand, cavitation sets in at a lower temperature near the surface of the radiator than at a large distance from it. As a result, the effect itself sets in earlier, then increases smoothly with t. On the other hand, for large values of δ the cavitation activity decreases with increasing t not only due to the increased pressure of the gas inside the bubbles and the concomitant decrease in their energy and rate of collapse, but also due to acoustic energy losses in the cavitation zone. This factor becomes increasingly significant with distance from the radiator, because the number of cavitation bubbles in the path of the sound wave increases. As a result, for large values of δ the effect attains its maximum earlier and then decreases more rapidly than for small values of δ.

The shift of the maximum of $\Delta P_0(t)$ to the left toward smaller values of t with increasing amplitude (Fig. 3, 1-3) is also atrributable to increased absorption.

The data obtained here confirm the conclusion that the increase in the elevation of the liquid in a capillary tube under the action of ultrasound in the presence of cavitation is mainly associated with collapse of the bubbles [6], rather than with their growth.

Thus, with an increase in the temperature all the properties of glycerin vary in such a way as to increase the rate of expansion of the bubbles and their sizes; the saturated vapor pressure increases, the viscosity decreases, and the surface tension and density both decrease (although the influence of the last two factors, as mentioned above, can be neglected). Consequently, if ultrasonic irradiation of the liquid in a capillary tube were attributable to bubble growth, this effect would have to increase or decrease over the entire range of investigated temperatures, depending on how the rate of bubble growth affected ΔP_0. However, the behavior of the curves $\Delta P_0(t)$ (Fig. 3) contradicts this conclusion.

On the other hand, if we assume that the ultrasonic capillary effect is associated with bubble collapse, then, as shown above, the results [including the curves $\Delta P_0(t)$] admit a logical explanation within the framework of the hypothesis developed in [4-6].

NOTATION

ΔP_0, excess pressure above meniscus in capillary tube in order to maintain meniscus at height of the usual capillary rise; σ, surface tension of liquid; α, gas content; P_v, vapor pressure; η, viscosity; d, diameter of capillary tube; δ, distance between capillary tube and ultrasonic radiator.

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TEMPERATURE FIELD OF THE ACTIVE ELEMENT OF A SOLID-STATE LASER WITH A LIQUID COOLING SYSTEM

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Results of a numerical solution of a nonstationary conjugate convective heat-transfer problem are presented. Temperature fields are determined in the coolant stream and in the body being cooled.

The distinguishing feature of solid-state laser operation in the continuous mode is the constant liberation of a part of the energy being pumped into the active element, as heat. Heating of the active element can result in a change in the laser generation characteristics, the appearance of substantial thermal deformations in the material, and failure of the element. In order to prevent overheating of the active element, a part of the heat being liberated there is eliminated through the side surface in the cooling system. In the majority of cases it is an optically transparent, external annular channel through which a liquid or gaseous coolant is pumped.

Existing methods for computing the temperature field in active elements [1, 2] are based on the traditional methods of computing the convective heat transfer in channels by using the Newton—Rikhman (Riemann) relationships in the equations or boundary conditions. However, it has already been shown in [3, 4] that such a formulation of the problem does not take account of the influence of the thermophysical properties and thickness of the wall material, as well as of the presence of internal heat sources, on the heat-transfer coefficient. Moreover, it is known that the index of refraction in the active element and the intensity of the thermal lens, that occurs, depend mainly on the temperature gradient over the radius and the length. The magnitudes of these gradients also determine the thermal stresses, disturbing the anisotropy of the active laser element.

In this connection, a conjugate problem must be solved to determine the temperature fields in the active element and coolant, and to take account of their mutual influence, i.e., a system of differential equations describing the heat transfer in the fluid and the solid must be solved. But it is first necessary to estimate for which cooling parameters is the traditional formulation of the heat-transfer problem possible by using the Newton—Rikhman relationships.

According to Lykov [3], it is customary to take the Bruhn number

$$\mathrm{Br}_z = \frac{\lambda_2}{\lambda_1}\,\frac{r}{z}\,\mathrm{Pr}^m\,\mathrm{Re}_z^n, \quad z \in [0,\ l] \tag{1}$$

as conjugate criterion.

If the Bruhn number is small ($\mathrm{Br}_z \leq \mathrm{Br}_{\mathrm{min}}$), then the convective heat transfer is computed by the traditional method. The quantity $\mathrm{Br}_{\mathrm{min}}$ is determined from estimates of the exact analytic solutions or by experiments. Often, the dimensionless number K, related to the Bruhn number:

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