GENERATION OF ACOUSTIC OSCILLATIONS DURING THE GROWTH AND BREAKOFF OF AIR BUBBLES

I. M. Fedotkin, A. V. Gukalov,
and S. V. Romanovskii

UDC 66.001-66.012-512.24

Problems associated with boiling and bubbling processes are investigated. It is established that acoustic signals occurring in the process of bubble generation are produced by pressure variations at the instant of growth and breakoff of bubbles.

Acoustical studies of boiling and bubbling processes are known to be impeded by the fact that temperature gradients, gas bubbles, foreign objects, and the resonance properties of the vessel and height of the liquid column all contribute to distorting the sound field.

In industrial situations boiling and bubbling processes occur in apparatuses of various dimensions and shapes with different liquid levels. The sound in such a vessel characterizes not only the process itself, but also the resonance characteristics of the vessel and the liquid contained in it. Multiple reflections of the acoustic signal from the walls produce interference distortions. To segregate the signal characterizing the actual state of the process from the sound generated under such conditions does not pose a simple problem.

Air bubbles in a liquid are good absorbers of acoustic energy, particularly when the resonance frequency of the bubble coincides with the acoustic frequency.

We consider the case of sound scattering by bubbles in a liquid, assuming that the scattering events at individual bubbles are mutually independent [1, 2]. The resonance frequency of an air bubble is given by the Minaert equation [3]

$$f=\frac{1}{2\pi a}\sqrt{\frac{3\gamma P_0}{P_1}}. \tag{1}$$

A number of equations are given in the literature for determining the scattering cross section σ of a gas bubble. At low frequencies the Rayleigh scattering law, or fourth-power (of the frequency) law, is valid:

$$\sigma=4\pi a^2\left(\frac{f}{f_0}\right)^4. \tag{2}$$

At resonance the scattering cross section does not depend on the size of the bubble:

$$\sigma=\lambda/\pi. \tag{3}$$

At high frequencies it is also independent of the frequency and is equal to the surface area of the bubble:

$$\sigma=4\pi a^2. \tag{4}$$

The effective scattering cross section, i.e., the total power of the scattered wave referred to the intensity of the incident wave, is given by the expression

$$Q_s=\frac{4\pi a^2}{\left[\left(\frac{\omega_0}{\omega}\right)^2-1\right]-\left(\frac{D}{\omega}\right)^2}. \tag{5}$$

It follows from (5) that at frequencies much lower than resonance ($\omega \ll \omega_0$) Q_s is close to zero. At a frequency coinciding with the resonance frequency, the scattering cross sec-

---

Kiev Polytechnic Institute. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 45, No. 1, pp. 86-92, July, 1983. Original article submitted April 22, 1982.

0022-0841/83/4501-0780$07.50

tion is the ratio of the average power absorbed by the bubble to the intensity of the incident wave:

$$Q_a = 4\pi a^2 \omega^2 / D^2. \tag{6}$$

The total effective cross section is the sum of the effective absorption and scattering cross sections $Q_t = Q_s + Q_a$, where

$$Q_s = \frac{4\pi a^2 \left[1 + \dfrac{\delta}{k_1 a}\right]}{\left[\left(\dfrac{\omega_0}{\omega}\right)^2 - 1\right]^2 + \delta^2(\omega)}. \tag{7}$$

We assume that the liquid contains gas bubbles of equal radius. The number of bubbles per unit volume is n. We determine the intensity of a plane wave transmitted through a layer of bubbles with a thickness d when the intensity I_0 of the incident wave is known.

A layer of area ds and thickness dx between the coordinates x, x + dx contains n(x)dxds air bubbles. The power absorbed by the bubbles in the layer is

$$dIds = -n(x)\, dx Q_t I ds, \tag{8}$$

hence

$$\frac{dI}{I} = -n_0(x)\, Q_t I dx, \tag{8'}$$

and so the intensity of the sound wave transmitted through the layer of thickness d is

$$Id = I_0 e^{-Q_s} \int\limits_0^\alpha n(x)\, dx.$$

The integral $\int\limits_0^\alpha n(x)\, dx = N_1 d$ represents the total number of bubbles in a volume of unit cross section with the thickness d of the bubble layer.

Denoting the average number of particles arriving per unit length by $\frac{1}{d}\int\limits_0^\alpha n(x)\, dx = N_1$, we obtain

$$I_\alpha = I_0 e^{-Q_t N_1 d}. \tag{9}$$

It follows from this result that the attenuation of the wave intensity by the bubble layer in 1 cm is

$$D = 10 \lg \frac{I_0}{I_1} = 10 \lg e N_1 Q_t = 4{,}34\, N_1 Q_t \text{ dB}. \tag{10}$$

If the bubbles do not have equal radii and can be divided into a certain number of groups according to size, the total attenuation is the sum of the attenuations at bubbles of each size group: $D = D_1 + D_2 + D_3 + \ldots + D_n$. In the general case the radii of bubbles in water have a Poisson distribution function: The number of bubbles per unit volume that have radii a, $a + da$ is equal to

$$n(a) = \frac{dN}{da} = A(la)^m e^{la}. \tag{11}$$

The fraction of the absorption due to bubbles with radii from a to $a + da$ is

$$dD = n(a)\, da Q_t(a), \quad D = \int\limits_0^\infty n(a)\, Q_t(a)\, da. \tag{12}$$

The main part of the absorption is associated with resonance-size bubbles. An important parameter is the Q, which is equal to the ratio of the resonance frequency to the width of the resonance curve between points 3 dB below the maximum of the curve.

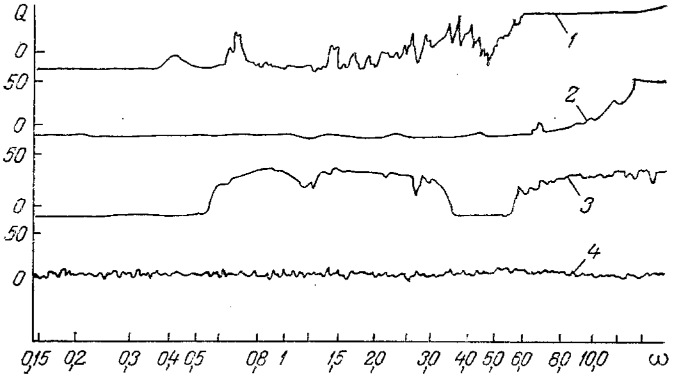

Fig. 1. Frequency-response curves of vessels: 1) rectangular metal vessel with dimensions 65 × 65 × 100; 2) the same vessel, its inner walls coated with a Porolon layer; 3) cylindrical glass vessel, wall thickness 3 mm, inside diameter 150 mm, height 200 mm; 4) the same vessel with fully developed nucleate boiling. Q, dB; ω, kHz.

The Q of a spherical bubble, a linear vortex filament of cylindrical bubbles, and a planar array of bubbles has been investigated [2]. A comparative estimate of the Q shows that the Q of an array of bubbles in comparison with a single sphere is greatly diminished. This means that the range of absorption frequencies is broader.

If Porolon [a Soviet-made acoustic insulation material] is submerged in a liquid, the pores in its honeycombed structure trap air bubbles, which create a spatial array of closely spaced bubbles. Porolon and water have similar acoustical parameters, whereas a very large difference exists between the acoustic impedances of the water and the gas in the Porolon pores. The gas bubbles in the Porolon differ not only in shape, but also in their dimensions (from 0.5 mm to 4 mm). It follows from (11), (12) that such a structure of gas bubbles should intensely scatter and absorb acoustic oscillations in the liquid over a wide range of frequencies. These characteristics permit Porolon to be used as an absorbing coating for the suppression of reflection from the walls and the absorption of resonant oscillations of the vessel.

To determine the resonance frequency of the structure, on the outside of each wall of the vessel we cemented a flat disk of TsTS-19 (PZT) piezoelectric ceramic, which served as an external source. The acoustic oscillations excited by the structural elements of the vessel were created by an external or internal source. Two types of excitation of the vessel were provided by means of a switch in the circuit. In external excitation the alternating voltage from an oscillator was supplied to the external source (to the cemented disks). In internal excitation the voltage was supplied to a radiating source situated inside the vessel. This arrangement could therefore be used to investigate the resonant properties of each wall and of the vessel as a whole.

The source and receiver situated inside the vessel with the liquid were in the form of spheres, 30 mm in diameter, made of a piezoceramic material of the same composition as the disks. The outer surface of the transducers was coated with a water-resistant lacquer. The transducers were mounted on the cover plate of the vessel on rubber packing seals.

The hookup of the 3G-18 audio oscillator and the N 110 autoplotter was such as to permit automatic recording of the frequency response. For this purpose the autoplotter was connected mechanically to the axle of the oscillator dial. The frequency of the oscillator was varied in the range from 20 Hz to 20 kHz by the drive motor of the autoplotter in synchrony with the movement of the tape.

It was established in the initial stage of the acoustical studies that the resonating action of the vessel asserts itself very strongly in the investigation of the bubble-generation process, particularly from a single center. The oscillograms and spectrograms of the process exhibit the resonating action of the structural elements of the vessel. In each vessel used for acoustical investigation of the process we obtained the frequency response, from which we were able to establish the possible frequency resulting from the resonating action of the vessel, as opposed to the process.

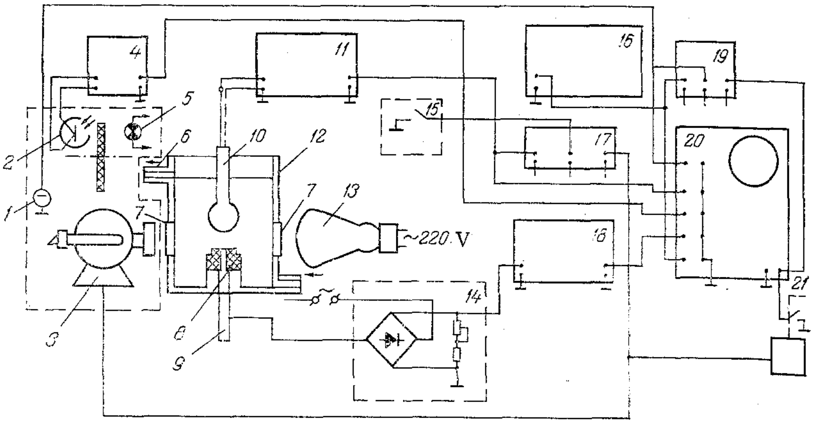

Fig. 2. Schematic of the experimental arrangement: 1) cluster switch; 2) photocell; 3) motion picture camera; 4) amplifier section; 5) lamp; 6) nipple; 7) viewing windows; 8) nozzle; 9) heater; 10) hydrophone; 11) noise meter; 12) measurement vessel; 13) illuminating lamp; 14) unit for switching nozzle and oscilloscope; 15, 16) power supply units; 17) amplifier; 18) unit for switching nozzle and oscilloscope; 19) synchronization unit; 20) oscilloscope; 21) switch.

The frequency response of the vessel when its inner walls are coated with a Porolon layer having a thickness of 1 cm shows that the resonance properties of the vessel in the frequency range 20-6000 Hz are somewhat pronounced. This part of the frequency response has a linear behavior (Fig. 1, trace 2). In the frequency range 6000 Hz-20 kHz the resonating action of the vessel is attenuated by 20-30 dB. In such a vessel the acoustical characteristics of boiling and bubbling processes are practically free of the influence of the resonance properties of the vessel.

The presence of bubbles in the liquid alters the acoustical properties of the liquid and the resonance characteristics of the vessel. In boiling and bubbling regimes where the gas content of the liquid is large (Fig. 1, traces 3, 4), the acoustical characteristics of such processes are free of frequency distortions elicited by the resonance properties of the vessel and reflection from its walls. Thus, in the investigation of the bubble-generation process from a single center it is recommended to use Porolon as an absorber. When the gas content of the liquid is high, it is no longer necessary to use Porolon.

Despite the vast number of papers published on the acoustics of boiling and bubbling processes, the cause of sound generation is still sketchy [3-7]. To study the origin of sound in connection with bubble generation, we chose a method for the synchronous comprehensive investigation of bubble generation from a single center. A schematic of the experimental procedure is shown in Fig. 2. The rectangular stainless steel vessel 12 has two viewing windows 7 in its side walls. The lower part of the vessel is provided with an opening, in which is placed the heater 8 or the nozzle 9. The vessel has a nipple 6, through which liquid is fed from the thermostat. The vessel is thermally and acoustically insulated with basalt wad. In the upper part is a cover plate, to which the hydrophone 10 is attached. To prevent contact with the liquid, the surface of the hydrophone is coated with a rubber layer, which has the same wave impedance as the water. The acoustic pressure measured by the hydrophone is transmitted to the noise meter 11, whose amplifier has a large input impedance, which is matched with the output impedance of the hydrophone and with the input of the oscilloscope 20. Such matching is important for the investigation of low-frequency oscillations. The oscillogram of Fig. 3 shows: the acoustic pressure in the vessel containing the investigated liquid, the conductometric signal [8], the timing sync pulses for the motion picture frames, the on-time of the camera time marker, and the time-marker signal. The oscillogram was recorded by a cathode-ray oscilloscope in the bubbling of air into water through a nozzle, which comprised an electrode insulated electrically from the vessel and connected through the device 14, 18 to the input circuit of the oscilloscope.

The acoustic oscillogram is displayed in the form of bursts of damped oscillations; the bubble inception time is accompanied by an abrupt drop in the conductivity as a result of the

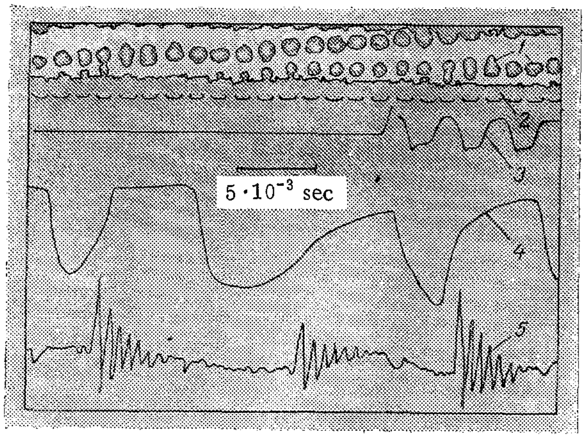

Fig. 3

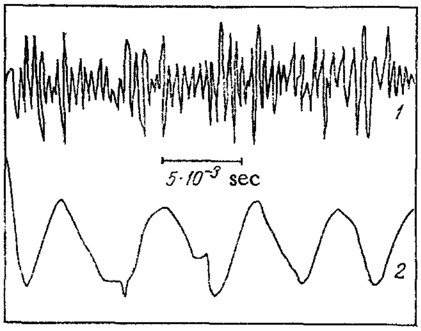

Fig. 4

Fig. 3. Simultaneous oscillograms and motion picture frames of the bubbling process from a single center: 1) motion picture frames; 2) frame-sync timing marks; 3) time-marker signal; 4) conductometric signal; 5) acoustic signal.

Fig. 4. Simultaneous oscillograms of the boiling process: 1) acoustic signal; 2) conductometric signal.

increase in the area of contact between the air bubble and the current-conducting tip part of the nozzle. The change in the acoustic pressure with the inception of a bubble is not as sharply pinpointed. This change corresponds to a very small pulse followed by a scarcely perceptible self-excited oscillation. The growth of the bubble is accompanied by a variation in the perimeter of its stem sitting on the hard surface of the nozzle. In the initial stage of growth the contact surface of the liquid with the nozzle decreases, diminishing the conductivity (conductometric oscillogram). Then with further growth of the bubble the stem constricts and breaks, increasing the contact surface of the electrode. The conductivity in the electrical circuit increases. The instant of breakoff of the bubble is weakly discerned on the conductometric curve. After breakoff of the bubble the nozzle electrode is not immediately freed of the air coating. This fact is clearly perceived from a comparison of the motion picture frames with the conductometric and acoustic signals.

An analysis of the acoustic oscillograms shows that the instant of bubbel breakoff in the vessel containing the liquid is accompanied by bursts of damped oscillations. The first pulse has the maximum amplitude and is directed upward. The instant of bubble inception is less pronounced in the oscillogram of the acoustic oscillations, and the first maximum pulse is directed downward.

It follows from these considerations that the acoustic signals are produced by the pressure variations at the instant of growth and breakoff of the bubble. The initial instant of bubble growth is accelerated, and at that time an excess (acoustic) pressure acts on the hydrophone in the vessel containing the liquid. In breakoff of the bubble the stem breaks in its narrowest part over the hard surface. Then the upper and lower parts of the stem draw together. The first breakoff pulse in the oscillogram is the result of the accelerated constrictions of the lower and upper parts of the stem. Consequently, the first pulse in the oscillogram has a negative spike relative to the initial growth of the bubble and depends on the amplitude of the first pulse and on the physicochemical properties of the liquid.

A similar pattern is observed in oscillograms of the boiling process. It is seen in the oscillograms that different noise characteristics correspond to different boiling regimes. For example, in underheated boiling (Fig. 4), sound is radiated both during the growth period and during the bubble collapse period. One period of the conductometric signal is accompanied by two damped oscillation bursts of the acoustic signal.

The experiment shows that a combination method can be used to investigate the process of breakoff of the stem of a gas bubble, as well as the acoustic oscillations associated with the nucleation and collapse of a gas bubble. The experimental results lead to the assumption that the combined electronic—acoustic method for the monitoring of boiling will be effective in the investigation of opaque liquids. The experiment also confirms the hypothesis that the acoustic effects in a liquid during boiling and bubbling are the result of pressure pulses, which promote different states of the bubble-formation process. The bursts of damped acoustic oscillations in a liquid are the result of the action of a single pressure pulse.

NOTATION

P_0, density of gas; $\gamma = C_p/C_V$, ratio of heat capacities at constant pressure and constant volume; P_1, density of liquid; a, radius of bubble; $D = 3pc^2/dpc$, damping factor of pulsating bubble oscillations due to acoustic radiation; $\omega_0^2 = 3pc/d^2p$, resonance frequency of bubble oscillations; $\delta(\omega)$, quantity characterizing damping of bubble oscillations due to absorption and radiation; C, sound velocity in liquid; N_1, number of resonant bubbles; Q_t, scattering cross section of resonant bubbles; A, l, m, experimentally determined coefficients.

LITERATURE CITED

1. L. F. Lependin, Acoustics [in Russian], Vysshaya Shkola, Moscow (1978).
2. D. E. Weston, "Sound propagation in the presence of bladder fish," in: Underwater Acoustics (V. N. Albers, ed.), Vol. 2, Plenum Press, New York (1967), p. 55.
3. R. I. Nigmatulin and N. S. Khibeev, "Dynamics of vapor—gas bubbles," Izv. Akad. Nauk SSSR, Mekh. Zhidk. Sred, No. 6, 56-61 (1976).
4. A. M. Kichigin and L. A. Kesova, "Inception of acoustic oscillations in the transition from surface to film boiling," Izv. Vyssh. Uchebn. Zaved., Energ., No. 8, 114-117 (1966).
5. V. V. Chekanov, "Generation of sound in boiling and its influence on the boiling process," Author's Abstract of Candidate's Dissertation, Engineering Sciences, Moscow (1966).
6. A. M. Kichigin, S. G. Povsten', Yu. N. Ostrovskii, and A. A. Krivenko, "Some possibilities for investigating the boiling mechanism by an acoustic method," Teplofiz. Teploenerg., No. 15, 60-64 (1969).
7. V. A. Gorbachenko and E. I Chetverikov "Mechanism for the investigation of acoustic pulses radiated by vapor bubbles," in: Research on the Physics of Boiling [in Russian], No. 1, Stravropol. Gos. Pedagog. Inst., Stavropol (1972), pp. 33-36.
8. I. M. Fedotkin and A. V. Gukalov, Inventor's Certificate No. 485371, "Device for investigating the growth dynamics of vapor and gas bubbles in a liquid," Byull. Izobret., No. 35 (1975).

PROPERTIES OF ADSORPTION MICROLAYERS AND THE KINETICS OF BUBBLE GROWTH ON A SOLID SURFACE

V. F. Stepanchuk* and M. L. Guris

UDC 536.423

The article contains an analysis of the kinetics of the growth of a vapor bubble on a solid surface in dependence on the thermophysical and capillary properties of the microlayer, which makes it possible to determine the parameters of the microlayer on the basis of experimental data on the kinetics of boiling.

Investigation of the kinetics of the growth of vapor bubbles at present is in one way or another brought into connection with the evaporation of a microlayer [1-7]. The physical nature of the microlayer and the regularities determining the growth of a vapor bubble have not been sufficiently studied.

The authors of [8] substantiated the existence of liquid microfilm of adsorptional origin under the bubble and presented functional correlations between the parameters of the bubble and of the adsorption microlayer. It was established that the shape of the surface bubble is determined by the properties of the adsorption film forming upon its origin, by its splitting

---

*Deceased.

Belénergoremnaladka, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 45, No. 1, pp. 92-95, July, 1983. Original article submitted April 2, 1982.