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THERMOACOUSTIC EFFECTS IN SURFACE BOILING LIQUIDS

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Abstract—The acoustic pressure levels and acoustic spectra in surface boiling of liquids have been studied experimentally. The experimental set-up is described and results presented on determining the origin of single vapour bubble sound pulse and the properties of total noise along the curve of nucleate boiling up to the critical boiling point. On the strength of the experimental study of surface boiling of pure liquids and binary mixtures, the existence of "thermoacoustic effects" in liquids is formulated, whose essence is the regular relationship between thermal and acoustic processes constituting liquid boiling.

NOMENCLATURE

a, thermal diffusivity;
k, thermal conductivity;
λ, latent heat of evaporation;
ρ, liquid density;
ρ', vapour density;
z, radius–vector modulus;
R, radius of vapour bubble;
$\dot{R}$, rate of bubble growth;
$\ddot{R}$, bubble growth acceleration;
σ, surface tension coefficient;
p, saturated vapour pressure;
p_0, hydrostatic pressure;
ΔT, liquid superheat, $= T_s - T_b$;
T_s, superheat temperature;
T_b, boiling point;
q, heat flux [MW/m^2];
q_0, initial heat flux at the instant of sound onset;
q_{cr}, critical heat flux;
P_{ac}, acoustic pressure (mV) or acoustic noise level;
ΔP_a, peak acoustic pressure in a single bubble pulse;
ΔP_z, pulse of acoustic pressure at a distance r;
T_0, temperature of bulk liquid [K];
τ, boiling duration [s];
t, time;
α, heat transfer coefficient [W/m^2 K].

SOUND CAUSES IN BOILING

RAYLEIGH [1] was the first who tried to reveal the causes of sound generation in liquid boiling. He arrived at an important equation relating the excess pressure ΔP in a bubble, liquid density ρ and time derivatives of the bubble radius (the values with dots above)

$$\Delta P = \tfrac{3}{2}\rho\dot{R}^2 + \rho R\ddot{R}. \qquad (1)$$

From the assumption of collapsing vapour bubbles being sound sources, Rayleigh has found that in this case very large finite pressure is attained, the main portion of bubble energy being transformed into acoustic energy. This Rayleigh statement has been developed by other investigators studying sound generation in cavitation when the Rayleigh assumption looks reasonable.

However in the case of superheated liquid the probability of sound generation by collapsing of vapour cavities becomes doubtful. The case is that when the bulk liquid is somewhat subcooled to saturation, no bubble collapse is observed at boiling though there is some sound.

At surface (local) boiling sound increases due to rapid growth of bubbles originating from liquid superheat in a thin boundary layer. This was proved experimentally by the authors of [2]. The experimental installation for one of the test series is presented in Fig. 1. In a transparent

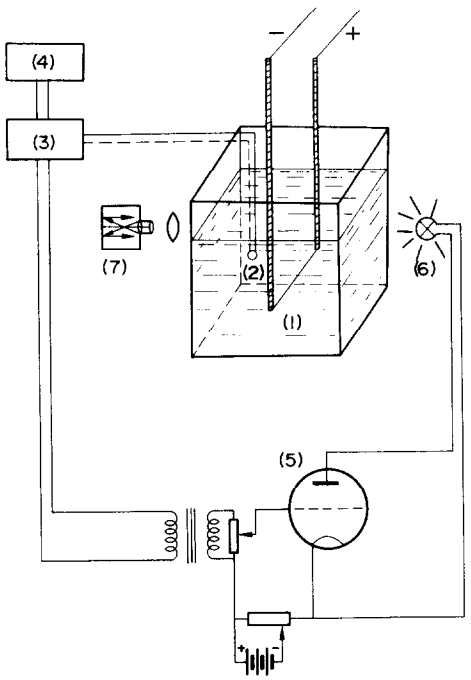

FIG. 1. Diagrammatic representation of apparatus for determination of the instant of sound pulse generation: (1) Transparent tank with distilled water; (2) hydrophone; (3) wide-band amplifier, (4) oscilloscope SI-1; (5) thyratron and connecting transformer; (6) flashing lamp; (7) camera with magnifier.

glass tank of parallelepipedon shape boiling was excited on a nichrome wire 0·1 mm dia. and 10 mm in length by supplying a preliminarily chosen heating pulse for the liquid to boil. Flash photography was employed using a camera with an open shutter, focused on the wire surface through a magnifier, and a flashing lamp "Luch-57". At the same time sound pulses were observed with the help of the oscilloscope CU-1. The sound pulse generated by a bubble was transformed into equivalent electric current by a spherical hydrophone. The parameters of the hydrophone of barium titanate piesoelectric ceramics were as follows: diameter of 15·5 cm, capacity of 4200 pF, sensitivity of 4·5 μV/μ bar. An electric pulse passed to the connecting transformer through the wide-band amplifier and ignited the thyratron which closed synchrocontacts of the flashing lamp "Luch-57". The lamp has been lighting up the wire for 2 μs during selfphotographing. The response time of the circuit was about 40 μs.

The idea of the experiment was very simple. If a sound pulse results from bubble collapse, the bubble would not be seen in the picture; if it appears during vapour bubble growth, then at rapid response of the circuit it would be observed in the photograph. The experiment has shown that sound is always generated within the bubble growth period. A sound pulse generated by fluctuating appearance of bubbles on the wire at liquid superheating has been used for synchronised photography. Herein a new bubble was distinctly seen each time. But its further possible variations including vanishing made no noticeable contribution to sound formation, presumably because of silent collapse of the bubble. Thus, sound appears within an abrupt growth of fluctuation-bubbles. Naturally, destruction of the heating surface material due to collapse proceeds at the same period. A detailed analysis of the dynamics of cavitational destruction would probably lead to the same conclusion. Recent literature [3] gives some interesting experimental evidence on this.

The conclusion of generation of a sound pulse within the period of vapour bubble growth is also proved by oscilloscopic observations. Hydrophone oscillograms indicate that each time a single pulse with only one maximum appears. If sound has also been generated at bubble collapse, two splashes would be seen on the screen with a gap between them being big enough so that they could be observed separately on the authors' equipment because the time of bubble collapse calculated by the Rayleigh formula was about 10^{-4} s.

Theoretical evidence of sound generation at

explosive growth of a vapour bubble leads to the conclusion that the maximum (peak) pressure of bubble growth depends on the rate of liquid superheat.

Inversion of Rayleigh equation (1) for a growing bubble with some assumptions introduced may show [4] that the rate of bubble growth increases rapidly at the initial stage of formation and attains an asymptotic stage for which the following relationship holds

$$R\dot{R} = \frac{6k^2}{\pi a\lambda^2\rho'^2}(\Delta T)^2 \tag{2}$$

where ΔT is the liquid superheat, ρ' is the vapour density.

Since $\dot{R} \ll c$, where c is the velocity of sound, the peak pressure at a distance of r from the bubble is $\Delta Pr = \Delta P^{R/r}$. For small bubbles the second term of equation (1) is infinitesimal, thus equations (1) and (2) for the peak pressure yield

$$\Delta Pr = \frac{3\rho}{2rR}\left(\frac{6}{\pi a}\right)^2\left(\frac{k\Delta T}{\lambda\rho'}\right)^4. \tag{3}$$

The rate of bubble growth has its maximum at the beginning when the bubble radius is close to a critical one. The radius of the critical bubble is determined from the Laplace–Gibbs equation

$$R_c = \frac{2\sigma}{p - p_0} \tag{4}$$

where σ is surface tension; p_0 is hydrostatic pressure and p is saturated vapour pressure.

Thus the value of the peak pressure in a pulse is close to the value

$$\Delta P_a \simeq \frac{36^2}{4\pi^2}\frac{\rho(p - p_0)}{\sigma r a^2}\left(\frac{k}{\lambda\rho'}\right)^2(\Delta T)^4. \tag{5}$$

The peak pressure appears to be greatly dependent on liquid superheat and, at a given superheat, the peak pressure depends on the saturated vapour pressure. These dependences have been tested experimentally for pool boiling of distilled water at normal and lowered pressures [2]. The experimental data confirm qualitatively formula (5).

Similar dependence of sound pulses of bubbles on superheat may be expected in boiling of binary solutions. It will be seen later that such assumptions have an experimental basis. However, calculation of the value of a combined integral sound for boiling of solutions is very complicated.

Preliminary experiments have shown that generation of a bubble is accompanied by sound pulses causing continuous noise with certain peculiarities due to the heat transfer laws at boiling [5]. These peculiarities are especially distinct for the boiling of binary solutions [6]. Hence the problem is to study the relationship between two simultaneous basic processes of boiling, i.e. thermal and acoustic.

In these studies aqueous solutions of homologous aliphatic alcohols (from methanol to n-pentanol) and some ketones were chosen as test fluids. The explanation is that the boiling mechanism of the above binary solutions, especially in the region of saturated boiling, have been thoroughly studied, [7, 8] etc. and very important results have been obtained by van Strahlen and other Dutch physicists. Therefore many of the thermophysical characteristics of these fluids are fully presented in literature not to mention the wide application of these fluids in various important technological processes. This facilitates the study of experimental data and allows the thermophysical properties available to be used for comparison of saturated and surface boiling.

EXPERIMENTAL SET-UP

The experimental set-up was designed for simultaneous investigation of thermal and acoustic properties in the boiling of pure liquids and solutions. Boiling was excited on a thin molybdenum wire 70 μm in diameter, which corresponds to the arithmetic mean of the British standard gauges Nos. 44 and 46 [9]. The method of investigating boiling by wire heaters has been used repeatedly in the past. This was probably the method used by Nukiyama in

1934 to discover "critical boiling". By applying the hot-wire method McAdams and others [10] have investigated in detail surface and saturated water boiling. The present author applied the hot-wire method to study surface boiling of water and aqueous solutions. In most experiments the temperature of the fluid bulk was kept constant and equal to the room temperature of 295 K.

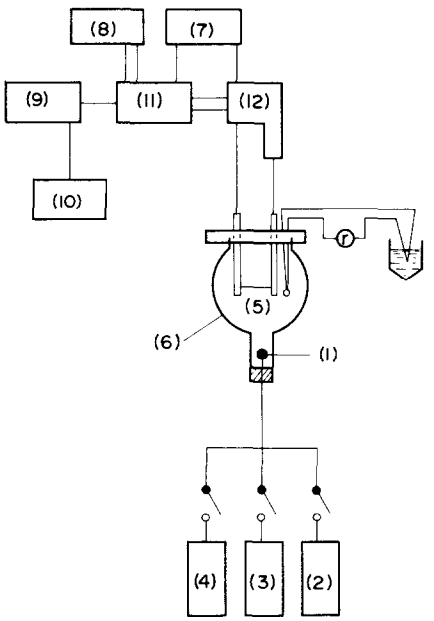

FIG. 2. Block-diagram of experimental set-up: (1) piezoceramic hydrophone; (2) acoustic spectrometer of audio frequency (40 Hz–20 kHz); (3) spectrometer of audio and ultrasonic frequency (7240 Hz to 292 kHz); (4) integrating instrument-millivoltmeter; (5) heating element; (6) 150 ml glass vessel; (7) thermal-treatment unit for heating element; (8) accumulator battery; (9) electronic control unit; (10) electronic stopwatch; (11) semiconductor d.c. amplifier; (12) auto recorders for measuring energy consumed by heating fuel element, Γ, galvanometer registering liquid bulk temperature.

The experimental installation included a sound analyzing unit which allowed the study of both integral noise characteristics, i.e. sound pressure P_{ac} and noise levels, and spectral parameters, i.e. instantaneous acoustic spectra.

The experimental installation made it possible to apply specific heat fluxes $q(\tau)$ in the form of heat pulses of predicted shape and time. This appears necessary because at long-time boiling the temperature of the fluid bulk as well as all the hydrodynamic and thermal conditions changed completely. Besides, thin wire exerts unusual "resistance" to boiling of solutions, presumably, due to quick boiling out of the low-boiling component near the wire. This was known to many of investigators long ago who took various measures, for example the method of Jarnet *et al.* [7] to avoid termination of boiling. In the present paper reproducible experimental results and good statistical data are obtained by choosing for excitation of boiling heat pulses of particular width and shape and conditioning heating elements (wires) by special methods of their treatment.

The experimental installation of which the block-diagram is shown in Fig. 2 allowed a number of binary systems to be investigated and regular interconnection between thermal and acoustic (integral and spectral) characteristics of boiling solutions to be detected. The phenomena are referred to as thermoacoustic effects in order to emphasize the interrelation between these two physical processes which take place at all phase transitions of the first kind with heat supply.

The experimental methods are based on simultaneous measuring of acoustic and thermal parameters of boiling fluids. Synchronous measurements have been ensured by automatic switching of the sound-analysing channel at boiling inception, this moment being a start for the next test.

Acoustic analysis of some pulses or noise was conducted as follows (Fig. 2). A hydrophone of barium titanate piezoceramics let through a rubber plug was connected with a special liquid waveguide at the foot of the instrument.

Such a switching required thermostating of the hydrophone and its sensitivity (4·5 μV/μ bar) remained constant within the experiment. Two special hydrophones 4·3 mm and 13 mm dia.

have been used in the experiment, the latter's capacity being 3500 pF.

The hydrophone transformed sound pulses into equivalent electric current and sent it to a sound-analysing block of the installation which consisted of two spectrometers, one of sf-type (2) for analysing noises of sonic frequency and the other of uf-type (3) for analysing noises of sonic and supersonic frequency. The scale of the second spectrometer allowed study of supersonic oscillations up to 292 kHz inclusive. This installation provided for switching one of the spectrometers and also parallel switching of both of them for thorough analysis of noise in a wide frequency range. Spectrum analysers allowed the amplitude of acoustic pressure or energy distribution by frequencies to be considered, i.e. the study of acoustic radiation spectrum. The measuring range of the uf-spectrometer was from 7240 Hz to 292 kHz and it was divided into 16 one third, octave bands. The sensitivity of uf-spectrometer, when the beam deviated by the whole working height of the screen, was equal to about 140 mV which is -15 db, where 775 mV are assumed to be a reference point. The frequency range of the sf-spectrometer is 40–20 kHz. Each scale division was 5 db with the dynamic range of scale 30 db. If necessary the sensitivity may be decreased with the help of a 50 db switch by steps of 10–0·2 db. This had to be done because sonic pressures attained very large values in surface-boiling of liquids. The curve of nucleate boiling corresponds to a wide range of acoustic pressure variation. Besides, in mixtures critical specific fluxes are considerably increased which at the same time is connected with great increase in sound. For example, in 1% aqueous solution of n-pentanol the sound level exceeds a similar sound level water by 56·2 db at the critical point. In the spectrometers a smooth adjuster-potentiometer is provided for in the range of 10 db without changing the sensitivity.

Integral sound characteristics, i.e. sound pressure or sound levels were measured by an integrating instrument (4). For this purpose cathode millivoltmeters of the type V3–4, V3–5 and V3–6 were used. The error in measuring the integral pressure levels by these instruments was 4 per cent from 40 Hz to 400 Hz, 2·5 per cent from 400 Hz to 20 kHz and 4 per cent from 20 kHz to 500 kHz. From the experiments the main spectrum of acoustic radiation in boiling is in the range up to 230 kHz. In this the intensivity of low-frequency components decreases with increasing heat flux and the energy spectrum shifts to supersonic frequencies. Therefore main spectral measurements have been carried out with the spectrometer SUCH in the range from 8 to 292 kHz. Integral measurements covered the whole range of frequencies beginning from 40 Hz. The total error of sound measurements was about 5 per cent. Thermal measurements produced a considerably smaller error (about 3 per cent).

The installation allowed simultaneous and separate spectral and integral acoustic measurements. Instantaneous spectra were photographed using 16 mm film, which provided continuous acoustic boiling spectra describing the whole of the nucleate boiling curve from the moment of the start of boiling at heat flux q_0 to the critical value of the heat flux q_{cr}. The latter was mainly accompanied by burn out of the heating wire, but in the case of boiling of water–alcohol mixture when the organic component concentration increased, no "burn-out" points were observed and stable film boiling set in with red-hot heat source. This phenomenon occurred stepwise.

Bumping takes place only during the initial period, when boiling begins as well as at extremely rapid heating, as was found in [11] when the tube was heated up to 500°F during 0·01 s. If the boiling curve covered the period 5–7 s which is quite sufficient for all the measurements be carried out with the existing inevitable inertia of the measuring instruments, then the stability of processes and reproducibility of measuring results would be quite satisfactory. These are the grounds for designing the thermal block of the installation.

The heating element (5) in the form of a thin molibdenum wire 70 μm dia. and 2×10^{-2} m in length has been fixed by special holders mounted into a textolite cap of the measuring vessel (6). The holders of chrome-plated copper tightly strained the wire with foil winding at its ends which provided tight contacts.

150 ml of test liquid were poured into a glass tank (6) of a special form with the throat pulled down which ensured liquid waveguide necessary for hydrophone thermostating within an experiment and other favourable conditions for acoustic measurements.

In order to study the structure of an acoustic field and effect of external factors on measurements, the heater may be moved vertically relative to the hydrophone and rotated horizontally. The results indicate that the acoustic pressure $P_{ac} \sim 1/r$ where r is the distance to the wire element with boiling excitation on it. From the preliminary investigation of the processes in liquids a constant distance of $r_0 = 3{\cdot}5 \times 10^{-2}$ m has been chosen for the hydrophone.

Proper preparation of the wire element for operation (conditioning) greatly influences the dependence of the acoustic pressure P_{ac} on the heat flux q and slightly the value of the maximum heat fluxes. It appeared useful for the wires to be calcinated in the air by 0·95 A current for 6·4 s and then immersed into an alcohol solution. The magnitude and duration of dc pulses for wire element conditioning were formed with an electronic unit of thermal treatment (7). For the period of thermal treatment the wires were put into a separate vessel to be insulated since even a slight convective motion of air changes considerably the required regime of calcination.

Accumulator battery (8) of 40 V was used for heating a wire element in liquids. The battery capacity allowed direct current up to 30 A to be obtained. In this case dc is necessary since ac experimentation does not ensure normal measuring statistics [8, 12].

For the correct measurement of surface boiling parameters the duration of an experiment is of significance especially when studying boiling of solutions with fast evaporation of one of the components due to volatility. It has been found experimentally that the optimum time for heating the wire should range from 5 to 7 s. For this time the solution concentration remains constant, and the temperature of the liquid bulk slightly increases. Thus the installation allows investigation of the processes over the whole of the surface boiling curve including the critical boiling region ("crisis I") and in some binary mixtures the region of radiational heating of the boiling liquid (red-form).

The heat flux $q(\tau)$ ("heating pulse") whose magnitude and shape are presented in Fig. 3 was produced by an electronic unit (9) and then supplied to the dc amplifier (11). The control unit allowed the heating duration to be changed and the pulse shape to be varied.

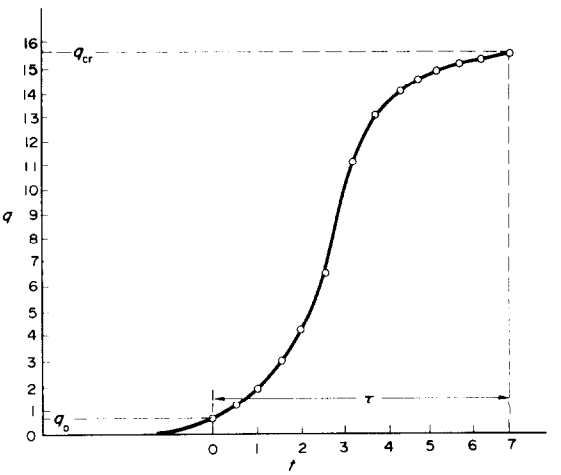

FIG. 3. Variation of heat flux with time (heating pulse).

Electronic control unit (9) is provided with semiconductor triodes P-15 and P-16. This unit in assembly with an electronic stopwatch (10) controls the duration and shape of the heating pulse, which then increases to the value prescribed for the next test. Here, in accordance with the problem, an automatic cut-off is set for the time-instant close either to the maximum acoustic pressure P_{ac} or to the value of the

critical heat flux q_{cr} which in pure components often causes the wire element burn out and, in some of the binary mixtures, development of a steady-state radiation heating.

The dc amplifier (11) is provided with powerful semiconductor triodes *P*-214B, *P*-210 and *P*-209 which are supplied with cooling radiators and operate at steady-state conditions. The thermal-treatment unit (7) consists of semiconductor triodes *P*-15. It is so arranged that one and the same battery supplying current to the wire element may send current pulses for wire conditioning and then automatically cuts off.

The power consumed in heating the wire element was registered by automatic recorders (12), type H340, of accuracy class 1·5 or by voltammeters, type MBA 47/5 of the 0·5 accuracy class, and the pulse length was measured by a stopwatch (10), PV-52 with an accuracy up to 0·01 s. The pulse length could also be calculated from the initial heat flux q_0 at which the test liquid started to superheat.

Figure 3 presents a typical heating pulse used by the authors to study boiling of water. The dc pulses, similar in their shapes but of different lengths, have also been used to investigate boiling of aqueous solutions of aliphatic alcohols and ketones which are to some extent considered in the present paper. The pulse shape was chosen carefully on the basis of physical conditions and aim of the experiment. The case is that while approaching the critical values of the heat flux q_{cr}, the heating rate should be varied so as to measure accurately the data at rapid and sharp change of the hydrodynamic conditions at this point.

EXPERIMENTAL RESULTS

Pure liquids and binary mixtures of constant composition

Osborne and Holland [12] have found single-valued correspondence between integral levels of acoustic pressure P_{ac} and the value of a heat flux within some region of its change. For some value of the heat flux the investigators have also observed a peculiar sound "saturation" when sound intensity did not change despite an increasing heat flux. Unfortunately, the investigators paid no attention to the boiling liquid properties because they attributed all the noise properties to "the hot wire" rather than to the boiling liquid. More recently a similar investigation has been carried out more thoroughly in water pool boiling at normal and lowered pressures [15].

Typical relationship $P_{ac} = f(q)$ is observed both in pure liquids and in binary system with the given concentration (x = const). A similar relationship is shown in Fig. 4. Here the results of sound and heat flux measurements are presented for boiling aqueous n-pentanol solu-

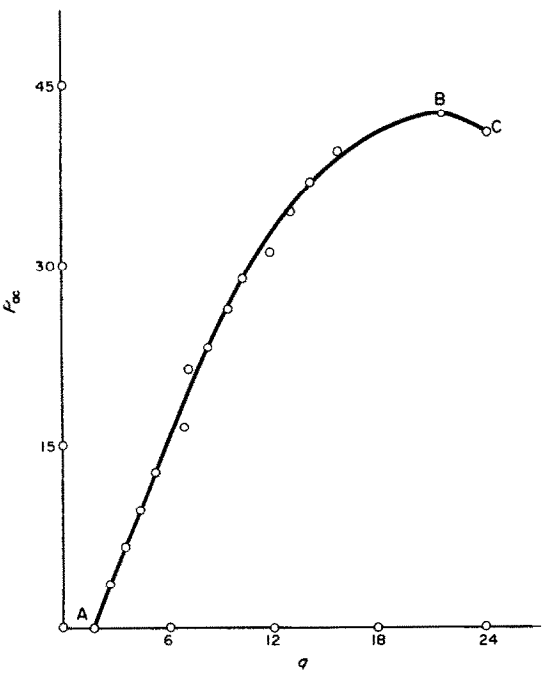

FIG. 4. Variation of acoustic pressure levels with the value of heat flux in surface boiling of binary mixture of constant composition (5 wt% of n-pentanol in water, T_0 = 295 K).

tion. The temperature of the liquid bulk was kept constant (T_0 = 295 K); here and below the concentration is given as wt.% with respect to

the weight of n-pentanol or other organic component.

The "curves of sound saturation" obtained have some peculiarities in boiling. With an excess of the organic component in a binary mixture, small maxima occurred in the curve $P_{ac} = f(q)$ at $q < q_{cr}$. In pure liquids and at small concentrations of the organic component in aqueous solutions the curves $P_{ac} = f(q)$ end with the "Burn-out point", according to Eckert [13]. With an excess of the organic component in aqueous solution stepwise transition is observed from nucleate boiling to "red-form" boiling on the heater which corresponds to film boiling and thus proceeds without heater overburning.

The high value of acoustic pressure appearing at water surface boiling and especially with some organic component additives in water is surprising. 10 mV voltage of the hydrophone corresponds to 222 N/m^2 of the author's installation. This is by 140 db higher than the conventional threshold of audibility ($P_0 = 2.10^{-5}$ N/m^2) in air.

Sound pulses become large enough for the level of noise intensity be registered at a definite heat flux (Point A, Fig. 4). Then the acoustic pressure P_{ac} increases to a maximum value $P_{ac} = P_{ac_{max}}$ (Point B, Fig. 4). Just before this point sound saturation becomes distinct, the sound level increases markedly slower than does the heat flux. If we terminate the graph with point B, then the curve looks like a photocurrent curve with a practically flat section of "saturation level" for a photoeffect. The boiling "crisis" and "burn out" point are observed at a comparatively small increase of the heat flux ($q_c > q_B$). At the boiling "crisis", in the vicinity of the "burn-out point" ($q = q_c = q_{cr}$) the acoustic level is somewhat lower than $P_{ac_{max}}$, and the acoustic fluctuation spectrum changes radically. The peculiarities of changes in the acoustic spectra are rather specific for different boiling curve sections. These peculiarities are connected with the mechanism of nucleate boiling and the boiling "crisis" in particular.

Figure 5 shows a set of instantaneous spectra which compose a current spectrum observed within an experiment from the start of boiling to the critical heat flux at the "burn out" point. In it are presented noise acoustic spectra for boiling an aqueous mixture with concentration $x = 5$ per cent of n-butanol by weight and liquid bulk temperature $T_0 = 292$ K. The pictures of spectra have been taken from the moment of sound generation at $q_0 = 2{\cdot}49$ MW/m^2 to the critical heat flux every 0·5 s. The structure of the instantaneous spectrum is very peculiar. It is characterized by high-frequency components decreasing in accordance with a non-exponential law, exponential decrease being typical for the noise spectra of hydrodynamic cavitation. The spectrum retains its typical form of a descending curve to the heat flux corresponding to the maximum acoustic pressure $P_{ac_{max}}$. Beginning from this moment the spectrum structure is so distorted that at critical flux the frequency components are distributed randomly. The maximum frequency of the acoustic spectrum increases with the heat flux density as is seen from Fig. 5. The growth continues up to the critical heat flux. The maximum frequency component appears to be typical for each maximum in the acoustic spectra of the homologous aliphatic alcohols. This resulting maximum frequency of the spectrum is shifted to high frequencies as the heat flux increases along the nucleate boiling curve. The frequency shift is very large and is most peculiar for the acoustic spectra of boiling. In boiling the binary mixture of butanol–water the maximum frequency shift (Fig. 5) is 117·1 kHz i.e. from 12·9 kHz to 130 kHz.

The intensity and frequency of the maximum component increases with the length of carbon chain (number of CH_2 radicals) in a molecule of the organic component of aqueous solutions of aliphatic alcohol. This phenomenon is mainly due to the fact that the maximum critical heat fluxes are shifted to lower concentrations of organic components with their absolute value increasing. Some molecular mechanism of both

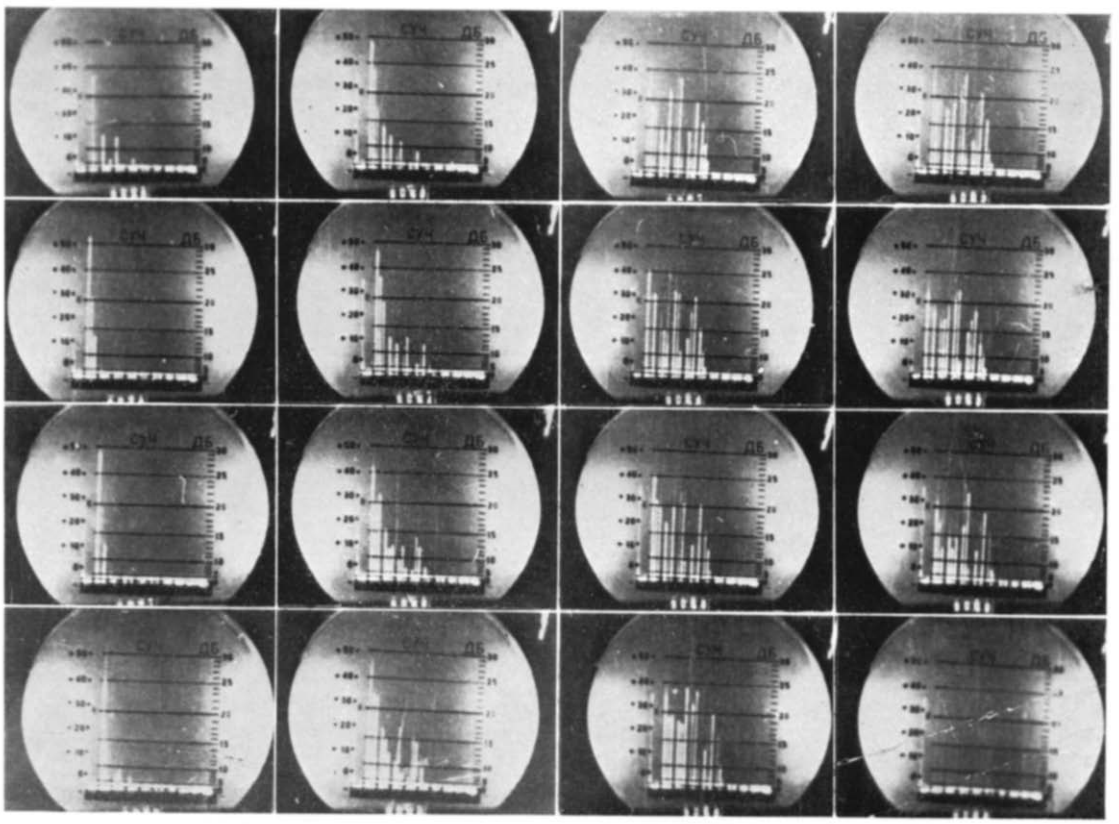

FIG. 5. Acoustic spectra in boiling of n-butanol–water mixture.

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thermal and acoustic energy transformation is present in the above binary systems at boiling.

Thermoacoustic effects due to changes in binary mixture composition

The main thermoacoustic effects in boiling fluids are revealed when acoustic (both integral and spectral) characteristics and appropriate specific heat fluxes fixed at the same time are compared at various concentrations over the whole region of mixing two liquids.

If we plot the "points of maximum acoustic pressure" $P_{ac\,max}$ (point B, Fig. 4) and simultaneously measured specific heat fluxes q vs. the composition of the boiling binary mixture, the relationship is peculiar for the aqueous solutions of n-butanol as shown in Fig. 6. Here

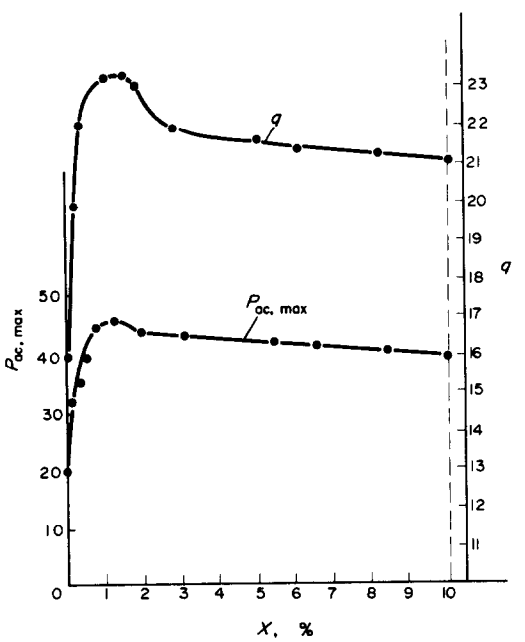

FIG. 6. Variation of maximum acoustic pressures of noise and heat fluxes with concentration in surface boiling of mixtures of n-butanol–water ($P_{ac\,max}$, mV; q, MW/m^2; x, n-butanol wt %).

the region of concentrations, up to phase separation is presented. After phase separation, thermoacoustic properties of binary n-butanol–water systems differ considerably at various heights in the gravity field as the system disintegrates into three parts (including the phase separation boundary) of different physical properties.

Each experimental point was obtained from averaging 12 measurements. As is seen from Fig. 6, at $x = 1{\cdot}2$ per cent the maximum $P_{ac\,max}$ values and characteristic maximum of the appropriate heat fluxes ($q = q_B$) are observed. The maximum sound at critical boiling point has also been observed at the same concentration, which will be discussed later. Besides, if in all the mixtures the heat flux is kept constant, its value being lower than q_B, for example 5–10 MW/m^2, then the maximum sound is observed in the vicinity of the above concentration [6]. All these phenomena may presumably be explained by the peculiarities of solution superheat within this region of concentration and by the properties of liquid evaporation. If the explanation is sought in the changing rate of vapour bubble growth, then the increase in acoustic pressures, heat fluxes being practically the same, should be explained by increasing rate of bubble growth in the above concentration range, though this contradicts literature data on saturated boiling. At any rate, increase in acoustic pressures at very small addition of an organic component to water ($x = 0{\cdot}1$–2 per cent) is connected with some internal properties of the binary liquid mixture and, in particular, with increase of possible superheat and peculiarities of the nucleation mechanism.

With the heat flux being constant in solutions of various compositions the heat transfer coefficients α do not remain constant, and at saturated boiling the curve $\alpha(x)$ for nonazeotropic binary systems has its maximum at some concentration. In azeotropic mixtures two types of curve $\alpha(x)$ occur heaving two extrema on both sides of the azeotropic composition [14]. This is, probably, due to liquid superheat peculiarities. In particular, in nonazeotropic and azeotropic systems with the maximum $\alpha(a)$ at low concentrations of an organic component in

water. superheats considerably increase at the minimum points of $\alpha(x)$. This presumably occurs at surface boiling too, which causes the sound level to increase when the boiling solution concentrations correspond to the minimum $\alpha(x)$ at $q = \text{const}$.

The maximum acoustic levels are observed at low concentrations of organic component of binary mixtures. At surface boiling the maximum critical heat fluxes also took place within the same regions.

Boiling crisis and boiling liquid acoustics

When studying acoustic pressures and spectra in the vicinity of "burn-out points", i.e. at critical boiling points, one of the important thermoacoustic effects appears. In pure liquids it is due to a certain transformation of the acoustic spectrum energy, and in binary systems may be attributed not only to the composition of the aqueous solution but also to the position of an organic component in the homological series.

To study this phenomenon, experimental results are presented of simultaneous measurements of acoustic pressures and maximum critical heat fluxes $q_{cr_{max}}$ for homological series of aliphatic alcohols and some ketones (Table 1).

Table 1. Maximum critical heat fluxes and appropriate pressures and concentrations of organic component in surface boiling of liquids

Liquid	X % Wt	q_{cr}, MW/m^2	P_{ac}, mV
water	—	15·81	19·4
methanol–water	25	16·93	27·9
ethanol–water	20	18·15	31·2
n-propanol–water	16	19·42	36·3
n-butanol–water	1·2	23·03	43·6
n-pentanol–water	0·8	26·61	55·1
acetone–water	12	16·37	33·2
methylethylketone–water	5	21·14	43·4

At liquid boiling crisis thermal effects are closely related to acoustic ones.

The study of $q_{cr_{max}}$ and acoustic level arrangement depending on the position of organic component of aqueous solution in homological series of aliphatic alcohols from methanol to n-pentanol shows that at surface boiling the absolute value of $q_{cr_{max}}$ increases and shifts to decreasing concentration of organic component in the mixture. Herein, the acoustic pressure levels appropriately increase and acoustic spectra vary causing increase in the number of high-frequency components and shift of the maximum spectrum frequency and energy maximum of spectrum to high frequencies. All of these phenomena are observed from 30% concentration of methanol to 0·8% concentration of n-pentanol.

Naturally, the mechanism of liquid surface boiling differs from that of saturated boiling. This is evident from the fact that at saturated water boiling the critical heat flux is 0·75 MW/m^2 [8], while at surface boiling it is 15·81 MW/m^2, i.e. as much as 20 times the previous value. The processes of energy transformation at surface boiling are connected with explosion-like growth of a vapour bubble which results in radiation of a sound pulse due to superheat and other thermophysical properties of liquid.

CONCLUSIONS

The analysis of experimental data shows that liquid surface boiling causes a number of thermoacoustic effects which may be generalized as follows:

(1) In pure liquids and binary mixtures of constant composition sound saturation proceeds by a typical curve. Acoustic noises increase from the minimum level at boiling to maximum one which always appears at some particular heat flux, the acoustic spectra being within a wide range of sonic and ultrasonic frequencies close to 300 kHz.

(2) Acoustic levels P_{ac} corresponding to maximum critical heat flux $q_{cr_{max}}$ are regularly distributed in aqueous solutions of aliphatic alcohol series and, probably, of other homo-

logous series. The regularity is that with increasing number of carbon atoms in a homolog the absolute values of P_{ac} and $q_{cr_{max}}$ also increase and shift to lower concentrations of organic component, the energy maximum of the acoustic spectrum falling in these composition range. Thus, thermal and acoustic properties are closely related to molecular composition of liquids.

(3) With increasing number of carbon atoms in the organic component of aqueous solutions of aliphatic alcohols, the concentrations (with respect to organic component by weight) decrease at which maximum levels of sound saturation $P_{ac_{max}}$ occur. Herein the acoustic spectra vary in such a way that the maximum frequency of the spectrum increases simultaneously with the sound intensity.

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EFFETS THERMOACOUSTIQUES À LA SURFACE DES LIQUIDES EN ÉBULLITION SUPERFICIELLE

Résumé—On a étudié expérimentalement des niveaux de pression acoustique et des spectres acoustiques aux surfaces de liquides en ébullition. On décrit l'installation expérimentale et on donne les résultats sur la détermination de l'origine de la pulsation sonore d'une bulle de vapeur unique et sur les propriétés de bruit total le long de la courbe d'ébullition nucléée jusqu'à la caléfaction. A partir de l'étude expérimentale de l'ébullition en surface de liquides purs et de mélanges binaires, on établit l'existence des "effets thermoacoustiques" dans les liquides dont la nature est liée aux processus thermiques et acoustiques accompagnant l'ébullition du liquide.

THERMOAKUSTISCHE EFFEKTE BEIM OBERFLÄCHENSIEDEN IN FLÜSSIGKEITEN

Zusammenfassung—Akustische Druckspektren und das Druckniveau beim Oberflächensieden in Flüssigkeiten wurden experimentell untersucht. Der Versuchsaufbau wird beschrieben. Die Ergebnisse in der Bestimmung des Ursprungs des Schallimpulses einer Einzelblase sowie die Eigenschaften des Gesamtgeräusches entlang der Siedekurve beim Blasensieden bis zur Siedekrisis werden dargelegt.

Basierend auf der experimentellen Untersuchung des Oberflächensiedens von reinen Flüssigkeiten und Zweistoffgemischen, wird die Existenz von "thermoakustischen Effekten" in Flüssigkeiten begründet; dies drückt sich aus in einer Beziehung zwischen den thermischen und akustischen Prozessen.

ТЕПЛОАКУСТИЧЕСКИЕ ЭФФЕКТЫ В ПОВЕРХНОСТНО КИПЯЩИХ ЖИДКОСТЯХ

Аннотация—Экспериментально исследваны уровни акустического давления и акустические спектры при поверхностном кипении жидкостей. Приводится описание экспериментальных установок и полученных с их помощью результатов по определению момента возникновения звукового импульса одиночного парового пузырька и свойств суммарного шума вдоль кривой пузырькового (ядерного) кипения вплоть до кризиса кипения.

На основе экспериментального изучения поверхностного кипения чистых жидкостей и бинарных смесей обосновывается существование в жидкостях «теплоакустических эффектов», сущность которых заключается в закономерной взаимосвязи тепловых и акустических процессов, составляющих кипение жидкостей.