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GENERATION MECHANISMS OF HYDRODYNAMIC AND THERMOACOUSTIC AUTO-OSCILLATIONS AT SURFACE BOILING IN CANALS

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Basing on the analysis of multiple combined, direct, other full-scale experiments including numerical ones, there have been revealed the generation features of two types of acoustic auto-oscillations at under-heated liquid boiling in tubes: hydrodynamic (HDAO) and thermo acoustic (TAAO). It is shown, that steam bulbs' formation at HDAO is initiated by the pressure stationary wave in the discharge phase, and at TAAO the collapse of all steam bulbs occurs under the compression of this wave. In the first case, steam is the working body at the thermal energy transformation into acoustic energy; in the second case it is liquid. The principal difference between these auto-oscillations manifests itself in the kind of their frequency-amplitude spectra. In contrast to HDAO, where only one mechanism of sound formation takes place, at TAAO there are two sound formation mechanisms acting simultaneously. At that, the periodic component of alternating pressure represents oscillations initiated by heat supply, and the noise component of the pressure is created by sound impulses, which are generated hydrodynamically by steam bulbs.

Generation mechanisms of hydrodynamic and thermo acoustic auto-oscillations were considered with the use of the experimental data [1-3]. Glass tubes performed the functions of canals in the experiment, which allowed visual controlling of the hydrophone location and filming of the boiling process. Identical cylindrical chambers with the diameter (42 mm) several times larger than the canal diameter were placed at the entrance and exit of the canal. The acoustically opened reflection boundaries of the longitudinal stationary wave in the canal were specified by the jump changing the square of the liquid-stream cross-section. Boiling within the length of the canal occurred on the heater parallel to the canal axis. Acoustic measurements were performed by a calibrated (with the sensitivity of 0, 51 mm V/Pa and even up to 20 kHz frequency characteristic) miniature (with the outer diameter of the piezoelement – 3, 4 mm) movable hydrophone inserted into the canal.

Fig. A presents the dependence graph of the relative sound pressure p/P_m upon the applied thermal load q/q_m with the hydrophone placed in the acoustic centre of the canal (in the loop of the pressure stationary wave at the oscillation excitation of mode I). Fig. B shows the curves of sound pressure distribution along the canal, received as a result of hydrophone moving, which correspond to the three points of the dependence graph $p/P_m = F(q/q_m)$: its first maximum «a», minimum «b» following it and the second maximum «c» (the direction of liquid movement in the canal is shown by arrow). The frequency-amplitude spectra of alternating pressure registered at the same points «a», «b» and «c» of the curve $p/P_m = F(q/q_m)$ are presented in Fig. C.

The first and the second maximums in the dependence graph $p/P_m = F(q/q_m)$ are determined by hydrodynamic and thermo acoustic auto-oscillations. The equal manifestation of one or the other type of these oscillations is the possibility of reaching high amplitude (of static pressure order) the stationary wave in the canal (curves «a» and «c» in Fig. B).

The registered distribution curves are asymmetric relative to the geometrical centre of the canal. It is due to the temperature and steam-content, which increase towards the exit of the canal causing the increase of two-phase medium compressibility and the decrease of sound speed in it. At that, the loops of stationary waves shift to greater compressibility. The above mentioned is proved by the second distribution curve «c», received at alternate changing the direction of the liquid stream in the canal (Fig. B). The result of data averaging of two curves is the distribution broken curve, the maximum of which coincides with the geometric centre of the canal. At the absence of the pressure stationary wave (point «b») the level of boiling noise towards the canal exit decreases monotonically due to the increase of sound adsorption under the increase of volume steam-content. The positive feedback acts through the pressure stationary wave at the considered types of acoustic auto-oscillations.

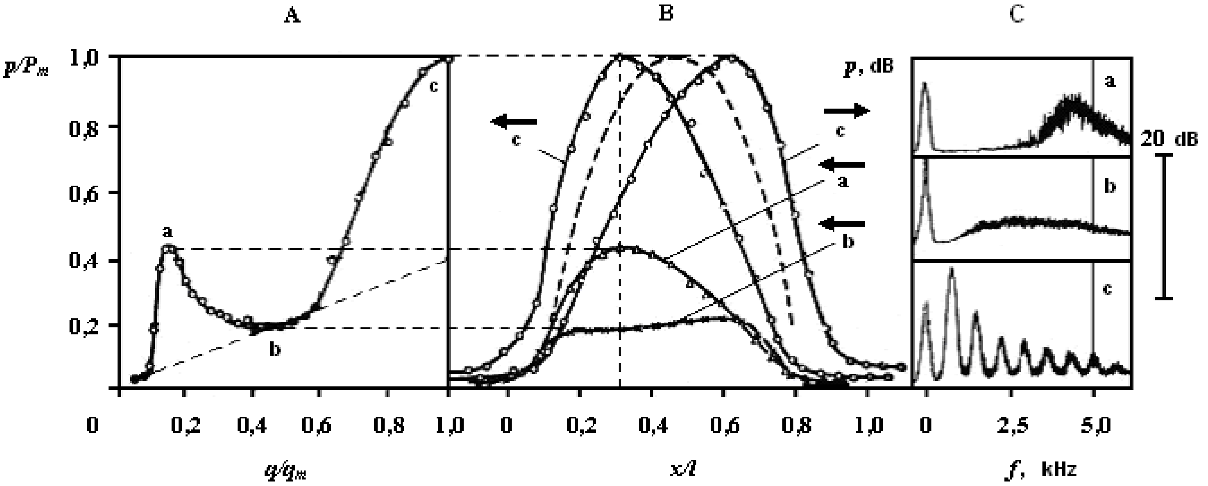

Fig. The results of combined experiments: the dependence of sound pressure relative volume upon the applied thermal load (A), the curves of the pressure distribution along the canal (B) and its frequency-amplitude spectra (C)

The principle difference of these auto-oscillations manifests itself in their frequency-amplitude spectra. In the spectrogram of hydrodynamic auto-oscillations «a» (Fig. C) there has been fixed a wide high-level maximum at the frequency of these oscillations. The spectrogram of thermo acoustic auto-oscillations «c» (Fig. C) contains a number of narrow maxima: the first one occurs at the frequency of these oscillations and the following ones at the frequency of their harmonics, that is to say, represents a "ruled " red-frequency spectrum. When the pressure stationary wave is absent the spectrogram of boiling noise «b» (Fig. C) has a very wide maximum of the low level, the frequency of which is determined by the average-statistic parameters of sound impulses exited by separate steam bulbs (under great scattering of these parameters it is close to the "white noise" spectrogram).

In the previous experiments [4-8] it was shown, that beyond the critical point within the non-wave zone $R << r << \lambda$ (R - radius equal in the volume of spherical bulb, r - distance to the control point, λ - sound wave length) the alternate pressure p, generated by a bulb of arbitrary shape, is determined by the Raleigh equation

$$\frac{p}{\rho'} = \frac{R^2\ddot{R} + 2R\dot{R}^2}{r} = \frac{\ddot{V}}{4\pi r} \tag{1}$$

(ρ' - liquid density, V - present bulb volume).

In the previous research [9, 10] we obtained the formula describing the dynamics of steam bulb volume change at under-heated liquid boiling

$$\frac{V}{V_m} = \left[\frac{1 - Ax - X}{1 - A(1+\alpha)}\right]^3, \tag{2}$$

where V_m - is the maximum bulb volume, $A = \exp(-\alpha)$, $x = \alpha t/t_m$ and $X = \exp(-x)$. At that, the constant α, dependent upon the ratio τ/t_m of "life" periods and bulb growth, is to satisfy the boundary condition

$$1 - \exp(-\alpha\tau/t_m) - (\alpha\tau/t_m)\exp(-\alpha) = 0. \tag{3}$$

From (1) and (2) it follows, that the sound impulse hydrodynamically exited by a steam bulb is calculated in accordance with the equation

$$p = \frac{3\alpha^2\rho' V_m (1 - Ax - X)\left[2(X - A)^2 - X(1 - Ax - X)\right]}{4\pi[1 - A(1+\alpha)]^3 r t_m^2}. \tag{4}$$

When the periods of bulb generation and collapse are equal, $\tau/t_m = 2$ and from (3) it follows, that $\alpha = 0$. In this case the formulae (2) and (4) represent equivocations of the $0/0$ type, the evaluation of which by the numerical method leads to the following correlations:

$$\frac{V}{V_m} = \left[\frac{t}{t_m}\left(2 - \frac{t}{t_m}\right)\right]^3 \tag{5}$$

and

$$p = \frac{3\rho' V_m}{2\pi r t_m^2}\left[-5\left(\frac{t}{t_m}\right)^4 + 20\left(\frac{t}{t_m}\right)^3 - 24\left(\frac{t}{t_m}\right)^2 + 8\left(\frac{t}{t_m}\right)\right]. \tag{6}$$

At under-heated liquid boiling steam bulbs create the alternate pressure p, which changes its sign twice: consecutively compression impulses (at the beginning of bulb growing), discharge impulses (when its volume is close to the maximum) and compression ones (at the end of the bulb collapse). Sound pressure reaches the maximums P_{m1} (+), P_{m2} (-) и P_{m3} (+) at the time moments t_{m1}, t_{m2} and t_{m3}. Under the above-mentioned conditions the formula (1) is true for sound exiting by integral steam volume of simultaneously generating and degenerating bulbs, which occurs at hydrodynamic auto-oscillations (HDAO).

The optimal condition of HDAO generation is the equality of time t_{m2} necessary for reaching discharge impulse the maximum P_{m2} to the period T of steam-liquid pole resonance oscillations in the canal

$$T = \frac{2l}{nc} \qquad n=1, 2, 3, \ldots \tag{7}$$

(l – acoustic length of the canal and c – average sound speed to the length in the two-phase medium). The point is that the stationary wave in the canal at discharge phase facilitating boiling process initiates the increase of a group of steam bulbs, which create the maximum discharge impulse within the period of time $t_{m2}=T$. At that he discharge sound impulse generated by alternate integral steam volume and acting in the phase of the pressure stationary wave, increases its amplitude. At this time the growth of a successive bulb group begins and all the phenomena repeat. Such is the mechanism of HDAO generation.

The beginning of steam bulb growth may slightly mismatch the moment of reaching the discharge wave maximum. Besides, the period of time t_{m2} of various bulbs is different. Both cause wide maximum in the frequency-amplitude spectrum of HDAO.

The above-mentioned is completely realized in the area of the first maximum in the dependence graph $p/P_m = F(q/q_m)$ (Fig. A). At the absence of the pressure stationary wave, dark points represent the experimental data. At the very beginning of the graph the period of resonance oscillations T is essentially smaller than t_{m2}, thus HDAO are not generated. The hydrophone registers boiling noise. As far as the heat flow density increases, the average volume steam content grows in the canal that leads to smooth decrease of c and increase of T (7). At that T, being less than t_{m2}, comes close to t_{m2}, resulting in HDAO antidumping (first light points in the graph). The further increase of heat load leads to the equality of T and the average (statistically) value. At this moment the HDAO level reaches the maximum (point «a» in Fig. A). Then T becomes much larger than t_{m2}, the amplitude of HDAO decreases up to their complete cessation (dark points on the right of the first maximum in Fig. A, the inclined broken curve in this figure represents the dependence of the boiling noise level upon the heat flow at the absence of any auto-oscillations).

The HDAO generating is possible only in relatively short canals, when the congruence $T = t_{m2}$ can be executed, as in long canals at the beginning of boiling process T is much larger than t_{m2}, further growth of heat flow sharpens this inequation.

The main difference between the onset conditions of HDAO and acoustic oscillations of the second type is the correlation opposition between their period T and the "life" time of steam bulbs. At HDAO $T = t_{m2} < \tau$ (time period t_{m2} is close to the time of bulb growth t_m). In the second type of auto-oscillations we have $T > \tau$ (often more than in one order). In the dependence graph $p/P_m = F(q/q_m)$ (Fig. A) these auto-oscillations cause the second quick increase of the sound pressure level, when as a result of further increase of heat load, average volume steam-content in the canal and the period of resonance oscillations T the inequation $T > \tau$ is already being fulfilled.

In contrast to HDAO, when only one sound-forming mechanism works on, at TAAO two such mechanisms act simultaneously. Herewith the periodic component of alternate pressure represents oscillations generated by heat supply, and the noise component of this pressure is created by sound impulses hydrodynamically generated by steam bulbs. The static pressure P_{st} in the canal has inverse effect upon the amplitudes of these components. In this rate, under the doubling of P_{st}, the amplitude of the alternate component becomes twice as much, and the amplitude of sound impulses decreases more than in one order [7, 8]. Therefore at $P_{st} > 2 \cdot 10^5$ Pa the alternate pressure registered with TAAO changes smoothly, without jumps caused by these impulses.

In actual practice we often deal with TAAO and very are with HDAO. Besides, in narrow ring canals (there the canal width coincides with the maximal dimension of steam bulbs) a third type of acoustic auto-oscillations can appear under boiling close to the first thermal transfer crisis. This type of generating oscillations by heat supply, principally different from TAAO, was revealed for the first time by B.V. Rauschenbach [11]. Such auto-oscillations are not enough investigated.

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