# THERMOMECHANICAL AND THERMOACOUSTIC SELF-EXCITED OSCILLATIONS

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It is well known that free temperature oscillations cannot exist in nature. The theoretical explanation of this fact is that the equation of heat conduction, unlike the equations of mechanics or electrodynamics, are not invariant under time reversal [1]. In the presence of periodic thermal perturbations (for example, repeated changes in the temperature head), however, forced temperature oscillations, which propagate in the form of heat waves, appear in the body [2-7].

In the last few years it has become clear that periodic mechanical, electric, and optical processes as well as processes of a different nature, in addition to thermal actions, are often responsible for the appearance of thermal oscillations in the system. The temperature oscillations arising in this manner, in their turn, lead to pulsations of the shape and dimensions of the body as well as its position in space, i.e., to mechanical vibrations.

The combination of thermal oscillations and mechanical vibrations is customarily termed thermomechanical oscillations (TMO). Thermomechanical oscillations were studied in 1829 by A. Travelian [8], and later by M. Faraday, A. Tyndal, J. Rayleigh, and A. S. Popov [9]. K. F. Teodorchik later studied this problem [10-13]. Interest in TMO has now increased appreciably as a result of the possibilities for intensification of heat transfer with its help. Here we call attention primarily to the works of V. M. Galitseiskii et al. [14]. Analogous studies have been performed by others also [15-19].

While studying oscillations of current-carrying wires, D. I. Penner and his coworkers discovered the phenomenon of parametric excitation of TMO [20-25]. The theoretical and experimental studies of [26-41] are devoted to the determination of the conditions for the appearance of self-excited oscillations under these conditions (TMSO). Section I is devoted to the analysis of the basic results obtained in the studies enumerated.

Intensive study of thermoacoustical oscillations (TAO) arising as a result of intercoupled temperature oscillations and high-frequency pressure pulsations in a continuous medium also started in the 1950s.

A series of works devoted to the most studied type of TAO – acoustic phenomena accompanying boiling and interaction of these phenomena with heat transfer between the heater and the boiling liquid – is studied [46-69]. Studies of parametric amplification of pressure and temperature pulsations in a liquid medium and the establishment of intense thermoacoustic self-excited oscillations (TASO), accompanied by a sharp increase in the coefficient of heat transfer $\alpha$ and the amplitude of the acoustic pressure $P_{ac}$, are of special interest [70-92].

In order to be able to use TAO in practical applications (for acoustic diagnostics of the operation of heat-exchange apparatus and for recording the onset of boiling of a liquid heat-transfer agent, increasing the intensity of heat transfer, and reducing scaling) and to eliminate some negative phenomena accompanying TAO, the reasons for the appearance of acoustic noise and the characteristic features of this noise under different conditions of boiling as well as the circumstances encouraging and inhibiting the excitation of TASO must be determined [68].

Section II is devoted to the current status of the problem of thermoacoustic oscillations.

## I. THERMOMECHANICAL OSCILLATIONS

1. Appearance and Characteristic Features of Some Types of Temperature Oscillations. As a first example we shall study oscillations of the temperature accompanying transverse oscillations of a thin heated cylinder. Since the rate of cooling of a heated body in a liquid

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or gas increases as the relative velocity v increases, the coefficient of heat transfer $\alpha$ depends on v: $\alpha = f(v)$. The character of this dependence can be determined in general form taking into account the fact that in the case of heat transfer under conditions of transverse flow around a cylindrical heater (in the region of small Re numbers) the criterion $Nu \sim Re^{1/2}$ [3]. From here it follows directly that

$$\alpha(v) = \alpha_0 + h\sqrt{|v|}, \tag{1}$$

where $\alpha_0$ is the coefficient of heat transfer of a stationary body; h is a constant that depends on the geometry and thermophysical properties of the body.

King confirmed, based on experiments with thin cylinders moving uniformly in a straight line, the validity of (1) and he established that under these conditions

$$h \simeq \sqrt{c\lambda D} \tag{1'}$$

(c and D are the specific heat capacity and diameter of the cylinder, $\lambda$ is the coefficient of thermal conductivity of the medium) [93].

When a body moves in a nonuniform manner heat exchange with the surrounding liquid is no longer stationary, but, as is easily verified, for sufficiently thin wires moving in a medium with insignificant acceleration the formula (1) can be used in the first approximation. Applying this formula to a thin heated cylinder, which undergoes low-frequency transverse oscillations according to the harmonic law $U = U_0 \sin \omega t$, and taking into account the fact that the modulus of the velocity $|\dot{U}|$ is a function of the frequency $2\omega$, we find the dependence of the coefficient $\alpha$ on the time:

$$\alpha(t) = \alpha_0 + \Delta\alpha_0 (1 + \cos 2\omega t), \tag{2}$$

where $\Delta\alpha_0$ denotes the amplitude of the pulsations of $\alpha(t)$ and is equal to

$$\Delta\alpha_0 = h\sqrt{|\dot{U}|_{\max}} = \sqrt{c\lambda}\sqrt{\omega U_0 D}. \tag{2'}$$

Representing the temperature T of the oscillating cylinder as a sum of its average value $\bar{T}$ and an oscillating term $\theta(t)$ — $T = \bar{T} + \theta(t)$ — with accuracy up to infinitesimals of high order we obtain for the temperature oscillations

$$\theta(t) = \theta_0 (\cos 2\omega t - \varphi). \tag{3}$$

The amplitude of the oscillations is determined by the equality [1]

$$\theta_0 = \frac{\Delta\alpha_0}{\sqrt{\alpha_0^2 + \left(2\frac{\omega C}{S}\right)^2}} \Delta T \tag{4}$$

(here C and S are the heat capacity and the area of the lateral surface per unit length of the cylinder; $T_0$ is the temperature of the medium; and, $\Delta T = T - T_0$).

The phase of the thermal oscillations $\theta(t)$ lags behind the phase of $\alpha(t)$:

$$\varphi = \mathrm{arctg}\frac{2\omega C}{\alpha_0 S}. \tag{5}$$

For practical applications the formulas (4) and (5) can be simplified [31], since $2C/S = 1/2\rho c D$, where $\rho$ is the density.

For most metals and alloys $b = 1/2\rho c \simeq J/cm^3 \cdot K$. At the same time, for thin cylinders $\alpha_0 = \lambda/2D$ [94], so that for $D \geq 1$ mm and $\omega \geq 1$ rad/sec the inequality $\alpha_0 \ll 2\omega C/S$ holds. Taking into account also (2'), we obtain for the amplitude of the thermal oscillations

$$\theta_0 = h' \sqrt{\frac{U_0}{\omega D}} \Delta T, \tag{4'}$$

where $h' = \sqrt{c\lambda}/b$ has the dimensions of $c^{-1/2}$. As regards the phase shift angle (5), in real systems thermal oscillations practically always lag behind the oscillations of $\alpha(t)$ by a quarter period:

$$\varphi = \frac{\pi}{2}. \tag{5'}$$

The expressions (3), (4'), and (5') were qualitatively confirmed in [30-34].

We shall now study an example of the generation of temperature oscillations by electric oscillations. Let an alternating current $J(t) = J_0 \sin \omega t$ flow along a long cylindrical conductor. Neglecting the skin effect, we have the following expression for the alternating heating $Q(t)$ (per unit length of the conductor):

$$Q(t) = \frac{J_0^2}{\lambda_{el}} \sin^2 \omega t = Q_0 (1 - \cos 2\omega t), \tag{6}$$

where $\lambda_{el}$ is the electric conductivity of the conductor per unit length and $Q_0 = J_0^2/2\lambda_{el}$ is the time-averaged heating.

Analysis has shown [1, 34, 37] that a nonstationary temperature field exists under these conditions within the cylinder:

$$T(r,\ t) = \bar{T}(r) + \Phi(r) \cos [2\omega t - \varphi(r)]. \tag{7}$$

Here $\Phi(r)$ is a function determined by a combination of Bessel functions of the first kind.

For thin cylinders, for which the temperature is virtually independent of the radius, (7) assumes the form

$$T(t) = \bar{T} + \theta_0 \cos (2\omega t - \varphi), \tag{8}$$

i.e., the temperature of the wire heated by an alternating current with frequency $\omega$ varies periodically with frequency $2\omega$, and the amplitude of these "electrothermal" oscillations is determined by a formula analogous to (4):

$$\theta_0 = \frac{Q_0}{\sqrt{(\alpha S)^2 + (2\omega C)^2}}. \tag{9}$$

The phase shift between $\theta(t)$ and $Q(t)$ is expressed by the known relation (5).

Taking into account the fact that under real conditions $\alpha S \ll 2\omega C$, we simplify (9):

$$\theta_0 = \frac{Q_0}{2\omega C} = h'' \frac{J_0^2}{\omega} \quad \left( h'' = \frac{1}{4} \lambda_{el} C \right). \tag{9'}$$

The condition (5), however, means in practice that the temperature oscillations $\theta(t)$ lag behind the current $I(t)$ by an angle $\varphi \simeq \pi/2$.

The examples presented show that both mechanical and electrical oscillations generate temperature oscillations, and the amplitude of the latter, as follows from (4') and (9'), decreases (although to a different degree) with the frequency of the primary oscillations. We note that in the case of "mechanothermal" oscillations $\theta_0 \sim 1/\sqrt{D}$, while for electrothermal oscillations $\theta_0$ does not depend on D.

We shall now study the reverse process — excitation of mechanical oscillations of the system by temperature oscillations.

2. Parametric Excitation of Thermomechanical Self-Excited Oscillations (TMSO). Necessary Conditions. Any elastic body, driven out of the equilibrium state, undergoes free oscillations with a characteristic frequency $\omega_0$, determined by the parameters (usually temperature dependent) of the system. For this reason, the appearance of thermal oscillations with frequency $\omega$ in the body leads to modulation of the corresponding parameters with the same frequency.

According to the theory of oscillations, if the condition

$$\omega \simeq \frac{2}{n} \omega_0 \ (n = 1,\ 2,\ 3,\ \ldots) \tag{10}$$

holds, parametric resonance (PR) arises in the system. Under these conditions, a correspond-

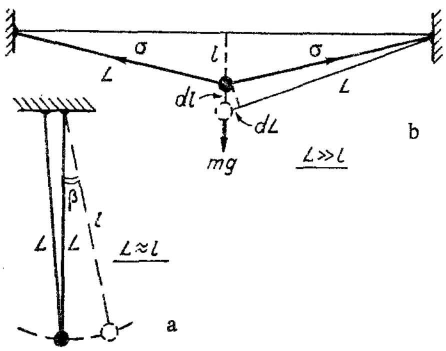

Fig. 1

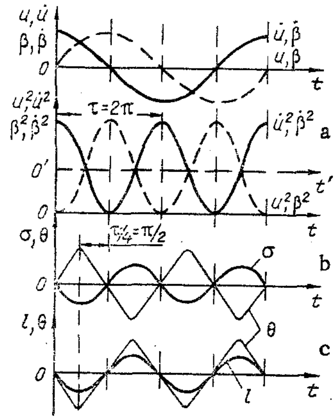

Fig. 2

Fig. 1. Thermomechanical oscillations of a heated bifilar pendulum (a) and elastic wire (b).

Fig. 2. Phase relations under conditions of TMO: a) mechanical oscillations of the wire U(t) and of the pendulum $\beta(t)$; b) oscillations of the temperature $\theta$ and modulation of the tension $\sigma$ of the elastic wire; c) oscillations of the temperature $\theta$ and modulation of the length $\ell$ of the pendulum.

ing relation [95], which is usually established automatically [96], should also hold between the phases of the fundamental and modulating oscillations.

The situation is more complicated with TMO, since the temperature oscillations themselves generate mechanical oscillations, so that their phases are strictly coupled. For this reason, in order for PR to arise in the system, aside from the condition (10), a second necessary condition — a phase condition — must also be satisfied.

We shall explain the essence of the phase condition for examples of an elastic wire and a mathematical pendulum heated with a current (Figs. 1 and 2).

In the case of a taut wire (Fig. 1b) undergoing transverse oscillations $U = U_0 \sin \omega_0 t$ the characteristic frequency $\omega_0$ is proportional to $\sqrt{\sigma/\rho}$ ($\sigma$ is the tension and $\rho$ is the density of the wire), while the coefficient of heat transfer $\alpha(t)$ pulsates synchronously with the function $\dot{U}^2(t)$, i.e., with the frequency $2\omega_0$. Correspondingly, the oscillations of the temperature $\theta(t)$ and modulation of the tension $\Delta\sigma(t)$, which are in antiphase, also oscillate with frequency $2\omega_0$ (Figs. 2a and b).

The current-carrying bifilar pendulum (see Fig. 1a) undergoes gravitational oscillations $\beta = \beta_0 \sin \Omega_0 t$, whose characteristic frequency $\Omega_0 = \sqrt{g/\ell}$. Here the square velocity $\dot{\beta}^2(t)$ and the coefficient $\alpha(t)$ varying in phase are characterized by the frequency $2\Omega_0$, and hence the temperature $\theta(t)$ and the modulation of the length $\Delta\ell(t)$ oscillate with the same frequency (Fig. 2c).

The rate of change of the oscillatory energy of the system accompanying modulations of the parameters $\sigma$ and $\ell$ is determined by the expressions [37]:

$$\frac{d}{dt} W_{\text{ela}} = \frac{\dot{U}^2}{2} \frac{d\sigma}{dt}; \quad \frac{d}{dt} W_{\text{grav}} = -\frac{\dot{\beta}^2}{2} \frac{dl}{dt}. \tag{11}$$

It follows from here that in order for PR to arise in the first case the modulations $\Delta\sigma(t)$ should lag behind $U^2(t)$, while in the second case $\Delta\ell(t)$ should lead $\dot{\beta}^2(t)$ (in both cases by $\pi/2$). Taking into account the phase relations between the oscillations $\Delta\sigma(t)$, $\Delta\ell(t)$, and $\theta(t)$, we conclude that for modulations of the parameter on which the frequency of the fundamental oscillations $\omega_0$ depends explicitly, in order for PR to arise $\theta(t)$ should lag in phase (approximately by an angle $\pi/2$) behind $\alpha(t)$; for modulations of the parameter on which the frequency $\Omega_0$ depends inversely, the oscillations $\theta(t)$ should lead $\alpha(t)$ by the same angle. This is the necessary conditions for the phases.

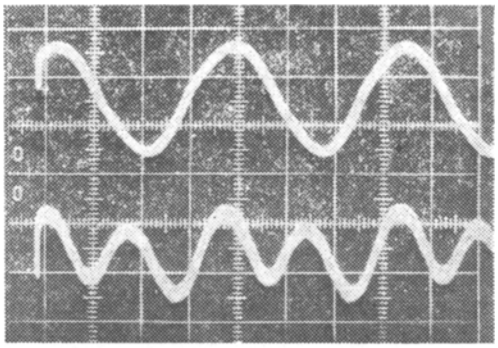

Fig. 3

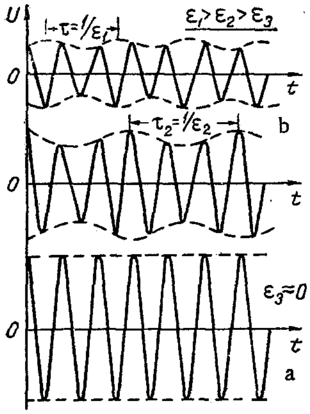


Fig. 4

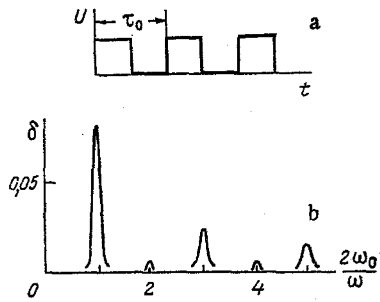


Fig. 5

Fig. 3. Oscillograms of mechanical (top curve) and temperature oscillations (bottom curve) of a wire heater in an underheated liquid near the resonance frequencies.

Fig. 4. Thermomechanical self-excited oscillations of a wire under conditions of pulsed heating: a) stationary oscillations; b) beats.

Fig. 5. Parametric amplification of oscillations: a) square modulation pulses (Meissner's function); b) dependence of the increment of excitation of oscillations $\delta$ on the ratio of the frequencies $\omega$ and $\omega_0$.

We shall now take into account the fact that under real conditions $\theta(t)$ always lags behind $\alpha(t)$. For this reason, elastic TMSO arise under transverse oscillations of the electric wire, but gravitational TMSO of the heated pendulum cannot be self-excited. This has been confirmed by diverse experiments performed in [34].

A new type of parametric amplification of TMO was discovered in [36], where the correlation between the changes in the temperature of an electrically conducting wire undergoing forced transverse oscillations and the frequency $\omega$ of these mechanical oscillations was studied. It turned out that for some so-called resonance frequencies $\omega_1$, $\omega_2$, $\omega_3$, ... a unique parametric amplification of the forced oscillations of the wire arises. At these frequencies the amplitude of the vibrations of the wire increases rapidly approximately by an order of magnitude, and the average temperature drops by 8-10°C. This is explained by the fact that near the indicated discrete frequencies the shift in the phases between the modulations of the tension [the latter are caused by periodic changes in the coefficient $\alpha$ and temperature pulsations $\theta(t)$ generated by them] and the oscillations of the wire reaches an optimal value $\varphi \simeq \pi/2$. As regards the condition on the frequencies, it holds automatically. The oscillation obtained in [36] (Fig. 3) demonstrates that both necessary conditions for PR hold.

Thus far we have discussed the excitation of thermomechanical self-excited oscillations by means of temperature oscillations, so to speak, "of mechanical origin." It is easy to verify that TMSO can also be excited by electrothermal oscillations.

Let an alternating current flow along a taut wire. If the frequency of the current $\omega$ is close to the characteristic frequency $\omega_0$ of transverse oscillations of the wire, then the periodic changes of the temperature $\theta(t)$ occurring in it have the frequency $2\omega_0$. Modulations of the tension $\Delta\sigma(t)$ caused by the temperature oscillations occur with the same frequency. Therefore the first necessary condition for PR holds. Since the phases of the transverse oscillations of the wire and the modulations of the tension are completely independent, the second condition holds automatically. Therefore TMSO should be excited in this system parametrically.

Such combined oscillations were obtained experimentally in [34], and an appreciable increase in the coefficient of heat transfer $\alpha$ was also recorded there.

This phenomenon was further studied experimentally by V. G. Krymova [38], who discovered that the rate of parametric pumping of energy and the intensity of TMSO grow significantly when square-shaped current pulses are fed into the wire. In this case the PR occurs not only when the optimal condition $\omega = 2\omega_0$ holds, but also in the case of the approximate equality

$$\omega \simeq \frac{2}{2n-1}\omega_0 \quad (n = 1,\ 2,\ 3,\ \ldots). \tag{10'}$$

We note that (10') differs from the usual condition (10), necessary for parametric excitation of oscillations, in that the denominator of the coefficient of the characteristic frequency $\omega_0$ is an odd number. As will be shown below, this fact is of fundamental significance.

One other effect was discovered in the indicated experiments: for sufficiently low frequencies $\omega$ of repetition of the current pulses (approximately in the interval from 1 to 7 rad/sec, the characteristic frequency of the wire $\omega_0 \simeq 15$ rad/sec) TMSO were excited for any value of $\omega$. In this case, however, the following peculiarities were observed: if the equality (10') holds strictly, stationary mechanical and temperature self-excited oscillations are established (their amplitude is all the more significant the smaller the number n) (Fig. 4a); when, however, the relation (10') holds approximately ($\omega = (2/2n-1)\omega_0 + \varepsilon$, $\varepsilon \ll \omega_0$), the range of both the mechanical and thermal oscillations undergoes periodic changes, unique "beats" (Fig. 4b), with a period $\tau \simeq 1/\varepsilon$. These effects will be explained below.

3. Energetics of Parametric Excitation of TMSO. In the preceding section two necessary conditions for the appearance of TMSO — frequency and phase — were established. There arises the question: are these conditions sufficient? The answer to this question requires a discussion of the energetics of the problem.

As the analysis performed in [34] showed, over the period $\tau$ the relative increment to the energy $\Delta W/W$ of the oscillating wire with temperature-induced harmonic modulations of its tension $\sigma$ is determined by the degree of modulation $\Delta\sigma_0$ and the phase shift $\varphi$:

$$\left(\frac{\Delta W}{W}\right)_\tau = \tau\Delta\sigma_0 \sin\varphi. \tag{12}$$

It is clear that $\Delta\sigma_0$ is proportional to $\theta_0$, and the coefficient of proportionality is the thermal coefficient of elasticity $\gamma = \frac{1}{\sigma}\left(\frac{\partial\sigma}{\partial T}\right)_L$:

$$\Delta\sigma_0 = \gamma\theta_0. \tag{13}$$

Substituting the value of $\theta_0$ from (4') and (12) into (13), we arrive at the relation for the increment to the energy per unit time:

$$\frac{\Delta W}{W} = h'\gamma\sqrt{\frac{U_0}{\omega D}}\,\Delta T \sin\varphi. \tag{14}$$

This last equation determines the rate of parametric pumping of energy into TMO. We shall now take into account the fact that for any system there is a threshold value of $(\Delta W/W)_{min}$, below which parametric excitation is impossible. Conversely, the more $\Delta W/W$ exceeds the threshold value the more rapidly the energy of the system grows and the more intense the TMSO are.

The height of the "threshold" $(\Delta W/W)_{min}$ for an oscillatory system depends on a number of factors: it increases with the "unbalance" of the frequencies $\varepsilon = \omega - 2\omega_0$, energy dissipation, and increase in the number n of PR in the condition (10), and it also varies strongly with the type of modulating oscillations.

Under all circumstances the excitation of self-excited oscillations in a real thermomechanical system requires that the following energy condition be satisfied in addition to the necessary conditions for the frequencies and phases:

$$\frac{\Delta W}{W} > \left(\frac{\Delta W}{W}\right)_{min}. \tag{15}$$

The energy threshold can be lowered, on the one hand, by improving the Q-factor of the oscillatory system. In the case of wire, to this end a small load with mass m can be suspended on it at the center. (The self-excited intense oscillations of such a current-heated wire were demonstrated in 1924 by N. I. Dobronravov and A. I. Shal'nikov. This effect was later explained by D. I. Penner [20]).

On the other hand, the energy injected over a period of the oscillations must be increased for this purpose. Here the character of the modulating oscillations plays an important role.

In a special study by the method of mathematical modeling, E. V. Borisov [38] established that for modulations conforming to Meissner's functions (Fig. 5a) the growth increment of the parametric oscillations is maximum, and in addition the repetition frequency of the "meander" should satisfy the condition (10') and the corresponding phase relation. If, however, the modulation frequency is related with the frequency of the system by the equality $\omega \approx (2/n)\omega_0$ (n = 2, 4, 6, ...), then for low degrees of modulation (even in the absence of dissipative losses) the increment to the oscillatory energy of the system is insignificant (Fig. 5b) (it should be noted that, as physical and mathematical experiments have shown, the character of the dependence of the increment of the excitation on the number n of the PR becomes more complicated as the degree of modulation increases). In the case of harmonic modulations a significant inflow of energy is observed only for n = 1, i.e., when $\omega = 2\omega_0$.

Based on these data we can understand the results of experiments with the wire heated with a pulsed current: in this case for any $\omega$ there exist numbers 2n − 1 and a relatively small $\varepsilon \ll \omega_0$ such that

$$\omega = \frac{2}{2n-1}\omega_0 + \varepsilon.$$

It remained to explain why beats appear in the self-excited oscillations when the equality (10') does not hold strictly, i.e., when $\omega = 2\omega_0 + \varepsilon$. Because of the difference in the frequencies, the phase shift between the modulations and the fundamental oscillations increases monotonically, and the factor $\sin\varphi$ appearing in (14) varies with the period $\tau \simeq 1/\varepsilon$. Therefore the energy flowing into the system varies with the same period, which is what leads to the beats in the self-excited oscillations. When, however, $\varepsilon \to 0$ and the period of the beats $\tau \to \infty$, stationary TMSO are established in the wire (Fig. 4a).

4. TMSO in Systems with Several Degrees of Freedom. In the case of a system undergoing several mechanical oscillations the TMO are much more complicated, and a number of features, for example, the dependence of the coefficient of heat transfer $\alpha$ on the type of oscillatory process, appear.

As an example we shall study the foregoing horizontal wire with a small load with mass m (see Fig. 1b). As a result of the fact that the coefficient of damping of free oscillations of the body in an air medium $\sim m^{-1}$, the Q-factor of the wire with the load is appreciably higher and the TMSO excited in it (under otherwise equal conditions) are much stronger than without the load. However, the fact that such an oscillatory system has several degrees of freedom is more important: elastic oscillations in the vertical direction and gravitational oscillations along a horizontal arc lying in a transverse plane (in this case the small mass is similar to a mathematical pendulum whose length equals the dip of the wire $\ell$) can appear in it. It should also be kept in mind that under the action of the pendulum motions of the load the wire clamped at the ends undergoes forced torsional oscillations.

For small dips $\ell \ll L$ the characteristic frequencies of elastic and gravitational oscillations of the indicated system are practically equal, i.e.,

$$\omega_{grav} = \omega_{tor} \simeq \omega_{ela} \simeq \sqrt{g/l}. \quad (16)$$

The equality $\omega_{grav} = \omega_{tor}$ is obvious, since $\omega_{tor}$ of the forced oscillations equals $\omega_{grav}$ of the perturbing force; the approximate equality of $\omega_{grav}$ and $\omega_{ela}$ is proved in [34].

How are TMSO excited and modulated in such a system?

For small random displacements of the heated wire from the equilibrium position, the wire starts to oscillate weakly. In the process, small temperature oscillations at the doubled frequency $2\sqrt{g/\ell}$, giving rise to modulations of the tension, which satisfy the necessary frequency and phase conditions for parametric excitation of elastic oscillations of the wire, accompanied by oscillations of the temperature $\theta(t)$ arise in it. In the presence of these oscillations (with the doubled frequency $2\omega_{ela}$) the length of the pendulum $\ell$ is modulated, i.e., the frequency condition is satisfied. Since the phases of the elastic and gravitational oscillations are independent of one another, elastic oscillations start to amplify parametrically the gravitational oscillations of the wire. In the process, based on the law of conservation of energy, the intensity of the first oscillations drops correspondingly. The unusual pumping of energy from vertical oscillations over into horizontal oscillations occurs.

Thus, at first elastic TMSO, which gradually transform into gravitational TMSO, exist in the system. However, the process does not stop here: the pendulum oscillations of the load generate torsional oscillations of the wire, and in the process the tension is modulated at the doubled frequency. For this reason, after some time reverse pumping of energy from horizontal over to vertical oscillations of the wire starts. The experiments of [34] show that such transitions can continue indefinitely. The character of the temperature oscillations becomes more complicated in the process: though on the average their intensity is conserved, the form of the oscillations becomes distorted.

This is apparently associated with the different conditions of cooling of the heated wire as it moves in the horizontal and vertical planes (in the latter case the wire is surrounded by a rising flow of heated air). On the whole the role of temperature oscillations reduces to compensating the energy losses owing to the current source. As regards $\alpha$, the measurements indicate that it increases by a factor of 2-4 when TMSO are established. It slowly oscillates during the periods when the energy of the oscillations is pumped from one degree of freedom to another.

The experiments show that when the electric wire is submerged in a cold liquid the intensity of the parametrically excited TMSO increases sharply (compared with an air medium), and the wire radiates a strong acoustic signal; the value of $\alpha$ in a cold liquid is approximately two times higher than in the gaseous medium with the same temperature [39].

We note that in some works [20, 21] it was suggested that parametric excitation of TMSO in linear electrical conductors was responsible for the appearance of the so-called "dancing of the wires." In [34], based on experimental and theoretical study of this hypothesis, it was concluded that under real conditions parametric buildup of oscillations of current-carrying wires can lead to very strong mechanical oscillations of stretched wires ("galloping"), when their diameter does not exceed 1-2 mm. Since the wires employed in electric power engineering have diameters of at least an order of magnitude larger, it can be assumed that TMO do not play a decisive role in the appearance of "dancing." Nonetheless the fact that they could affect the development of the "galloping" process has not been excluded.

## II. THERMOACOUSTIC OSCILLATIONS

In this section we shall study thermoacoustic oscillations (TAO) accompanying boiling in a large volume (Sec. 1) and accompanying flow of boiling liquid in channels (Sec. 2). The mechanism for excitation of thermoacoustic self-excited oscillations (TASO) will be studied in Sec. 3.

1. Mechanism for the Production of Acoustic Noise Accompanying Boiling. Over the last 40 years a series of experimental studies of the character of the acoustic noise accompanying the process of boiling has been performed. Nonetheless, there is still no general agreement regarding the mechanism responsible for the generation of an acoustic field. One of us recently suggested the general concept of the formation of acoustic waves accompanying heating of a liquid up to certain states — "preboiling," underheated and saturated boiling [43].

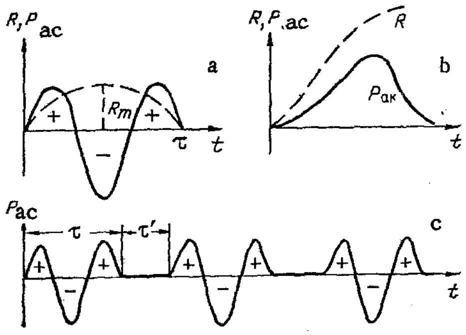


Fig. 6

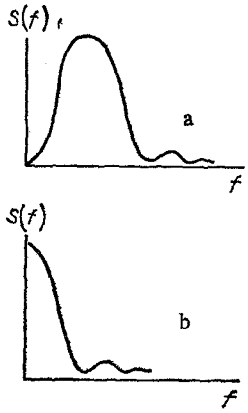


Fig. 7

Fig. 6. Qualitative dependences of the acoustic pressure pulses from separate bubbles of steam under conditions of underheated (a) and saturated (b) boiling and in the case of a sequence of periodically forming bubbles at an active center of underheated boiling (c).

Fig. 7. Qualitative picture of the spectra of acoustic pulses accompanying underheated (a) and saturated (b) boiling.

It is now generally acknowledged that noise accompanying heating of a liquid up to the boiling point and subsequent developed boiling is generated by bubbles whose volume V changes. Indeed, according to hydrodynamics [74], the simplest emitters of sound are bodies with variable volume embedded in a continuous medium. At distances $r \gg \lambda$ ($\lambda$ is the wavelength of the sound wave) the variable part of the pressure $P_{ac}(t)$ is given by the relation

$$P_{ac} = \frac{\rho}{4\pi r} \ddot{V}(t), \tag{17}$$

where $\rho$ is the density of the medium. Applying this formula to spherical bubbles ($V = 4\pi R^3/3$), we transform it into the form

$$P_{ac} = \frac{\rho}{r} R(2\dot{R}^2 + R\ddot{R}), \tag{18}$$

where R is the radius of the bubble. It follows directly from (18) that an appreciable acoustic pulse is usually initiated by quite large bubbles, though in [67] it was proposed that under conditions of saturated boiling sound is emitted by vapor bubbles at the earliest "explosive" stage of growth.

In addition, since vapor bubbles cannot form in underheated liquid, but a melodic sound, so-called "singing," can be heard in the preboiling state, it must be assumed that in this regime the sound sources are microscopic bubbles of gas which are always present in real liquids. As shown by Minnaert [42], such bubbles can undergo free spherical oscillations with the characteristic circular frequency

$$\omega = \frac{1}{R}\sqrt{\frac{3\gamma P_0}{\rho}} \tag{19}$$

(here $P_0$ is the static pressure, while $\gamma$ equals the ratio of the heat capacities $c_p/c_V$).

For air bubbles in water at normal pressure the frequency of the sound emitted by the bubble, as is easily verified, equals

$$f = \frac{0{,}66}{D}\ \text{kHz}, \tag{19'}$$

where D is the diameter of the bubble in cm.

Since water cannot contain very large gas bubbles, the audible sounds are emitted by bubbles whose sizes range approximately from $D_1 = 1/3$ mm to $D_2 = 1/3$ cm. Correspondingly, the acoustic frequencies range from 2 up to 20 kHz.

The chief reason for the excitation of such a spherical oscillator is evaporation of liquid in it as the liquid is heated: the destruction of the mechanical equilibrium of the bubble generates unusual self-excited oscillations of the vapor-gas bubble. Thus, raising the temperature of the liquid excites many sound emitters – small gas bubbles, each of which transmits a harmonic acoustic wave; their frequencies are of the order of several kHz. Ultimately, the characteristic singing of a "chorus" of gas bubbles, indicating the approach of boiling of the liquid, is audible.

When the temperature of the heater is further raised, the stage of underheated boiling appears. By this time the gas bubbles have been completely removed from the liquid and bubbles of steam start to form in the layer of liquid at the wall. Such bubbles at first grow, but, once they reach some size $R_m$, they enter the region of cold liquid and become degraded. This entire cycle is repeated with a period $\tau$, inversely proportional to the magnitude of underheating $\Delta T_{unh}$. According to (19) this means that the indicated bubbles of steam emit acoustic pulses. The integrated sound field, generated by many "pulsating" bubbles formed in active centers, is the noise of underheated boiling [68].

The general form of the spectrum of this noise can be determined by analyzing the formula (19): for small R the pulse is positive ($P_{ac} > 0$), while conversely, for $R \simeq R_m$, where $\dot{R} \simeq 0$, the pulse is negative (rarefaction) $P_{ac} < 0$. Therefore over the lifetime $\tau$ of a bubble the sign of the pressure in a pulse must change twice: compensation–rarefaction–compression (Fig. 6a). This character of the pulse has been confirmed in experiments [52].

To find the form of the acoustic spectrum of such a pulse $P_{ac}(t)$ must be represented in the form of a Fourier integral. To obtain a qualitative solution, however, we shall employ the general theory of spectra [97]: the spectrum of an aperiodic, sign-alternating pulse is continuous, and its maximum falls on a frequency $f_m$ that is the inverse of the period of oscillations of the pressure in the pulse (as is clear from Fig. 6a, this period equals approximately $2/3\tau$). The maximum at the center is weak, because the number of sign changes in the pulse is small.

Since not one, but a series of approximately repeating bubbles forms in active centers, according to [97] the spectrum becomes discrete, but in the process the segments of the line spectrum fall completely on the curve of the continuous spectrum of a single pulse. In practice, because of the inexact periodicity in the appearance of the next bubble, the noise spectrum accompanying underheated boiling is usually continuous and has a wide principal maximum and narrow, equally spaced, additional maxima. The presence of many centers increases the integrated intensity of the noise, but does not change the character of the spectrum.

As the temperature of the heater is further increased, the regime of saturated boiling, in which the steam bubbles arising grow monotonically up to macroscopic sizes, starts. Applying (19) in this case, we conclude that at first, for small R, the pressure is positive ($P_{ac} > 0$) and increases. In what follows, when the stage of "asymptotic" growth starts and $R \sim t^{1/2}$, the bubble continues to emit a compression pulse, whose magnitude drops with time as $t^{-1/2}$. Ultimately, the bubbles emit pulses of the form shown in Fig. 6b. The difference in the form of the pulses $P_{ac}(t)$ also affects their spectra: in the case of a pulse with a constant sign the spectrum has a maximum at the frequency $f_m = 0$. Figure 7 shows spectra of the pressure pulses emitted by isolated bubbles.

We shall make one other remark: under conditions of monotonic heating of a liquid up to the onset of saturation the degree of its underheating decreases, and the lifetime $\tau$ of the bubbles increases. For this reason the frequency $f_m$ of the maximum of the acoustic spectrum shifts monotonically to $f = 0$. Therefore, the character of the noise under conditions of underheated boiling changes continuously, until saturated boiling appears and the "tonal" quality of the noise becomes stationary. This conclusion agrees with the experiments of [52].

Thus, the boiling regime of a liquid can be judged from the character of the acoustic noise. The following experimental fact can also be understood: the loudness of the noise associated with underheated boiling is much greater than in the case of saturated boiling. The main reason for this lies in the fact that most of the acoustic energy accompanying saturated boiling falls into the inaudible, infrasonic region.

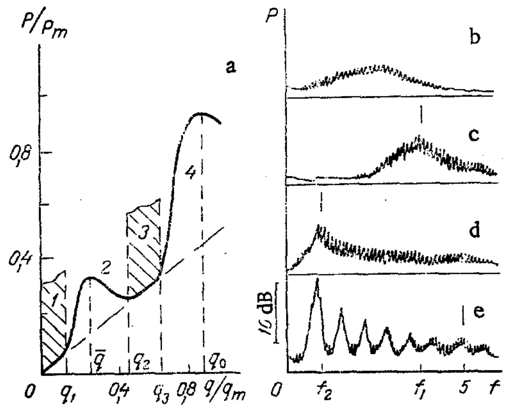

Fig. 8. Character of the acoustic noise of a boiling (with underheating) flow: $P_{ac}$ versus q (a); the noise spectrum in the regions 1 and 3 (b), region 2 (c), and region 4 (d, e). f, kHz; p, dB.

In conclusion, we note that the foregoing picture of sound generation is predicated on the fact that the liquid occupies an unbounded volume. Under real conditions, because of the finiteness of the dimensions of the vessel containing the liquid and because the vessel has characteristic frequencies, additional resonant phenomena are superposed on the indicated picture. It is quite difficult to take them into account in general; this can be done only in the simplest cases of a vessel with a regular geometric shape, in particular, accompanying boiling in a narrow cylindrical pipe.

2. Thermoacoustic Oscillations Accompanying Boiling of a Liquid in Pipes. Different types of channels (pipes), along which liquid heat transfer agents flow, are employed in power plants. Since the liquid moving in the pipe is an elastic medium, in accordance with the assumptions of hydrodynamics standing waves with definite discrete frequencies can arise in it [98].

If, in the process, the liquid boils, then vapor bubbles appear at active centers on the inner walls of the pipe, and because the volume of a bubble changes nonuniformly the bubbles are elementary sources of sound. Ultimately, a complicated nonstationary thermoacoustic field forms in the pipe.

This field and its effect on heat exchange have been studied by many authors [49, 50, 70-73, 75-89]. The most detailed study of TAO accompanying boiling in pipes was conducted in [68, 90, 91]. In these works $P_{ac}$ was determined at different points in a pipe and the dynamics of vapor bubbles were simultaneously recorded optically (with the help of FÉU); a system of thermocouples enabled finding the temperature distribution in the flow of boiling liquid.

All this enabled establishing the empirical dependences of the acoustic pressure $P_{ac}$ and its spectrum on the heat load q, the flow velocity v, the static pressure $P_0$ in the system, as well as the relation between the changes in the volume of a bubble and the phase of the acoustic pulse emitted by it.

To clarify the nature of TAO in a cylindrical pipe with an underheated-boiling liquid, we shall study in greater detail the typical dependence of $P_{ac}$ on the heat load q (Fig. 8a) [92].

Analysis of this curve reveals the most significant features of the acoustic noise of the boiling flow in an acoustically wide pipe (when its diameter D is of the order of the wavelengths of the sound waves λ emitted by the vapor bubbles).

The curve $P_{ac}(q)$ indicates that the entire interval of bubble underheated boiling is best divided into four regions.

In region 1 — small heat loads ($q < q_1$) — the acoustic noise is virtually "white," i.e., the spectrum is continuous and uniform with hardly noticeable peaks at the characteristic frequency $f_B$ of the vapor—liquid column in the channel (Fig. 8b). The acoustic pressure $P_{ac}$ grows linearly with q. There is no standing wave of elastic pressures of the medium in the channel.

In the region 2 ($q_1 < q < q_2$), as the heat load q increases, the acoustic pressure $P_{ac}$ rapidly increases and reaches a maximum at some $\bar{q}$, and then drops off smoothly. The frequency spectrum remains continuous, but is characterized by a wide maximum at a definite frequency $f_1$ (Fig. 8c). The sharpness of this maximum depends on q and is highest for $q = \bar{q}$. The pressure in the channel, as the measurements showed, indicates the existence of a standing wave, whose amplitude is maximum when $q = \bar{q}$, in this region.

Region 3 ($q_2 < q < q_3$) is similar to the first region; here there is also no standing wave, and the spectrum of the acoustic signal is identical to the spectrum of region 1 (Fig. 8b). The only difference between this region and the first one is that the acoustic accompaniment is louder.

Region 4 ($q > q_3$) is characterized by a fast increase in the acoustic pressure $P_{ac}$, while the spectrum is distinguished by the existence (at $q = q_0$) of a sharp maximum at a definite frequency $f_2 \approx 1/2\ f_1$ (Fig. 8d). The noise associated with boiling transforms into an intense "whistle." As the load q is further increased, maxima at frequencies of subsequent harmonics start to appear in the noise spectrum (Fig. 8e). As q approaches the critical load $q_{cr}$ the whistle vanishes, and the loudness of the sound drops rapidly.

The physical nature of such complicated thermoacoustic phenomena in pipes with a locally boiling liquid was qualitatively determined in [37, 63, 92].

We note first of all that in the case under study we have a complicated oscillatory system consisting of two subsystems: A) a collection of gas bubbles alternately increasing in size and collapsing and B) an elastic column of liquid that can undergo hydrodynamic oscillations with large amplitude. Both subsystems are intercoupled, and the character of their coupling, determining the overall thermoacoustic picture, depends on the thermophysical conditions, primarily, q. The subsystem A consists of a collection of N (equal to the number of boiling centers) elementary acoustic emitters, transmitting acoustic pulses with amplitude $\sim R_m^3/\tau^2$ (where $R_m$ is the maximum radius of a bubble and $\tau$ is its lifetime) [64]. It is well known that under conditions of underheated boiling the average values of $R_m$ and $\tau$ and hence the amplitude of the pulses also are virtually independent of the heat flux q. Therefore in the A subsystem only the number of emitters, which is proportional to $q^2$, depends directly on q [99].

The oscillations of the B subsystem consist of standing waves of the pressure, whose frequencies are multiples of the fundamental frequency $f_B$, which is determined by the length of the channel L and the sound speed c:

$$f_B = \frac{c}{2L}. \tag{20}$$

We shall now take into account the fact that in a two-phase medium the sound speed c depends on the vapor content X (in reality, as V. E. Nakoryakov et al. showed [61], the sound speed in a two-phase flow is a complicated function of the parameters of the system, but for our purposes we can confine our attention to simplified thermodynamic models) (Fig. 9a), while the latter depends on the load q, so that $f_B$ is a function of q (Fig. 9b). The amplitude of the standing waves is determined by the total energy fed into the two-phase column by acoustic pulses.

We call attention to the following fact. Vapor bubbles can "build up" a standing wave in a channel in two fundamentally different ways: first, when the bubbles send compression pulses in phase with the elastic longitudinal oscillations of the two-phase column, i.e., directly, and second, indirectly, when the total volume of the vapor bubbles, i.e., the vapor content X, periodically changes with the frequency $f_B$ (or a multiple of it). In the process, the oscillatory parameter of the B subsystem – the speed c of propagation of elastic waves in the channel – is modulated. When the corresponding phase condition is satisfied, TASO are excited parametrically in the pipe.

We now return to the analysis of the dependence $P_{ac}(q)$ presented in Fig. 8. The usual noise of underheated boiling, consisting of the superposition of acoustic pulses, generated in a disordered fashion by vapor bubbles forming and collapsing in active centers, is recorded in region 1. In this case the B subsystem plays a negligible role in the general generation of sound: the chaotically following compression and rarefaction pulses cannot excite a standing wave in the channel. On the other hand, since the bubbles emit pulses in a disordered fashion, the integrated sound intensity $J = P_{ac}^2$ grows in direct proportion to the number N of these elementary emitters. But, as noted above, $N \sim q^2$, so that $P_{ac}$ is proportional to q, as one can see from Fig. 8a.

We shall now study the region 2, where the values of the heat loads q fall into a neighborhood of $\bar{q}$ where the frequency of the elastic oscillations of the vapor–liquid column in the pipe $f_B$ equals the repetition frequency of the compression pulses ($P_{ac}^+ > 0$). We shall explain this in greater detail.

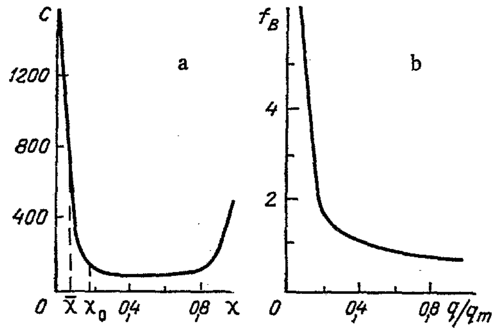


Fig. 9. Dependence of the sound speed c on the vapor content (a) and of the characteristic frequency $f_B$ on the heat load (b). c, m/sec.

Each bubble emits an acoustic pulse, shown in Fig. 6a. After the bubble collapses, a period of quiet starts, the duration $\tau'$ of which decreases as the temperature head $\Delta T$, depending on q, increases. Experiments show that this situation continues up to a definite value of $\Delta T^*$, at which the quiet time $\tau'$ of the center remains practically unchanged and falls into the range (1/3-1/2) $\tau$. For this reason, for sufficiently large q the series of vapor bubbles generated and collapsing at the same active center generates in the continuous medium pressure pulsations, whose qualitative character is shown in Fig. 6c.

As follows from this figure, each center of boiling emits unsymmetric pressure oscillations, and the experiments show that the repetition frequency of compression $f_A^+ \approx 1/3\ \tau$ is approximately twice the repetition frequency of rarefaction $f_A^-$: $f_A^+ \simeq 2f_A^-$.

As regards the frequency $f_B$ of elastic oscillations of the two-phase column, according to (20) it depends only on the sound speed c(X) determined by the vapor content. For this reason, as the heat load q increases, the frequency $f_B$ drops, so that for some value $\bar{q}$ the frequency $f_B$ equals $f_A^+$. In this case the partial frequencies of the A and B subsystems are equal to one another. According to the theory of oscillations, the coupling in the system (A + B) increases sharply and the (usual) resonance of coupled oscillatory subsystems appears.

In our case this means that, first of all, elastic oscillations of the B subsystem synchronize the moments at which bubbles appear and collapse in different active centers; second, during the time intervals when the emitters of A subsystem generate positive pressure pulses ($P_{ac}^+ > 0$) compression occurs in the two-phase column B. In other words, the bubbles exert a force on the continuous medium, building up the standing wave during its compression half-period. It is significant that the oscillations of the A and B subsystems are in phase.

When the heat load is further increased $q > q_2$, the frequency $f_B$ decreases, and an "unbalance" between the partial subsystems A and B appears, the resonance vanishes, and we fall into the region 3, where the noise in the channel is once again created by only the A subsystem, i.e., bubbles are formed and degraded chaotically. But now the numbers of centers N are larger than in region 1, so that the noise is correspondingly louder. Characteristically, the experimental points $P_{ac}(q)$ continue to fall along the same straight line as in region 1. We now turn to the analysis of the more interesting region 4.

<u>3. Parametric Excitation of Thermoacoustic Self-Excited Oscillations.</u> When the heat load is increased and approaches the value $q_0$, while the vapor content X correspondingly approaches $X_0$, the frequency $f_B$ decreases and reaches a value close to $f_A$, i.e., it approaches the repetition frequency of the rarefaction pulses generated by the bubbles: $f_B \approx f_A^-$ (Fig. 6c).

Therefore the partial frequencies of the A and B subsystems in region 4 are equal, so that resonance once again appears in the system, but this time the resonance is parametric. The standing wave arising here synchronizes the creation and degradation of vapor bubbles, energy is transferred from A to B during the compression half-period of the standing wave, but in the process the bubbles, as they collapse, emit a rarefaction pulse. Therefore, in this case, the pressure oscillations of the A and B subsystems are in antiphase, but the vapor content decreases and the oscillatory parameter c and the frequency $f_B$ increase.

It can be stated that in region 4 the chief oscillations are oscillations of the pressure in the B subsystem, while pulsations of the bubbles modulate these oscillations. Since the frequencies of the main and modulating oscillations are equal to one another, when the phase condition is satisfied parametric resonance should appear in the complicated system, as a result of which TASO are established. Here the vapor bubbles play the role of a valve: as they collapse, they transfer to the two-phase column the energy accumulated by them as a result of being heated by the heater.

We note the following important fact. As already mentioned above, if under the condition (10) the coefficient n = 2 (which is true in the case under study), the pumping of energy is very weak. But, because of the fact that in a neighborhood of the point $X_0$ the modulations of the parameter c are unsymmetric — c grows rapidly as X decreases, while when X increases c does not change (Fig. 9a) — strong parametric pumping of energy into the B subsystem occurs and the range of the oscillations of the standing wave grows rapidly.

It remains to check whether or not the phase condition holds in this case. It is shown in [37] that when the vapor content X and the sound speed c in the two-phase medium change, the oscillatory energy W of an isolated column varies according to the law

$$\frac{dW}{dt} = \frac{\eta^2}{2}\frac{dE}{dt}, \quad (21)$$

where $\eta$ is the relative compression of the medium, E is the modulus of compression, and $c = \sqrt{E/\rho}$.

It follows from (21) that for parametric increase of the energy W the modulus E and the sound speed c must lag in phase (in the best case by the angle $\Psi = \pi/2$) behind the pressure-determined compression $\eta$. On the other hand, the corresponding changes in the rate of vaporization or condensation give rise to changes in the pressure:

$$\frac{dX}{dt} = -\beta P_{ac}, \quad (21')$$

where $\beta$ is a constant that depends on the properties of the liquid.

But since in the interval from 0 to $X_0$ the sound speed c and hence the compression modulus E of the vapor—liquid medium decrease in proportion to the vapor content X, the relation (21') can be transformed, to a first approximation, into the form

$$\frac{dE}{dt} \simeq \beta' P_{ac}, \quad (21'')$$

indicating that the periodic changes in the modulus E(t) lag in phase behind the acoustic pressure $P_{ac}(t)$ by an angle $\pi/2$. At the same time the relative compression $\eta$ of the medium varies in phase, according to Hooke's law, with the oscillations of the pressure in the pipe:

$$\eta(t) \sim P_{ac}(t).$$

From here we conclude that oscillations of E(t) lag in phase by an angle $\pi/2$ behind oscillations of the compression $\eta(t)$, i.e., there is an optimal phase relation of the parametric pumping of energy.

Thus, in a boiling flow in region 4 elastic oscillations of the two-phase medium (B subsystem) are the main source of sound, and these oscillations control (feedback) the operation of the "valve" (A subsystem), periodically making it possible for energy to flow in from the heater. This is a typical self-excited process.

It is obvious that when the heat load is further increased significantly $q > q_0$ the vapor content X will shift appreciably to the right of the point $X_0$ (Fig. 9a), the conditions for parametric amplification of oscillations of the B subsystem are degraded, the standing wave is damped, and the intensity of the acoustic signal drops off rapidly. This usually occurs shortly before the onset of boiling.

In conclusion it should be noted that further study of the thermomechanical and thermoacoustic oscillations will enhance their practical applications in power generation and other areas of modern technology.

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