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ACTION OF VIBRATIONS ON HEAT AND MASS TRANSFER IN BOILING

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The state of the art of the works known in the literature and concerned with the influence of vibrations of structures of plants and artificially initiated vibrations in working liquids on the processes involving boiling is analyzed. The authors discuss theoretical and experimental results on the influence of frequencies and amplitudes on the internal characteristics of boiling, namely, the initiation of a vapor phase, the superheat in boiling, the growth and separation of vapor bubbles and the frequency of their occurrence, the density of nucleation sites, and also on the value of the heat fluxes and on the heat-transfer coefficient. Application of vibrational actions for intensification of heat- and mass-transfer processes is shown to be promising.

Introduction. The methods of intensification of heat- and mass-transfer processes in modern technologies by implementing pulsating regimes in the working volume of a plant or by applying vibrations to the basic flow field of a medium are among the promising techniques. Pulsations and vibrations are inherent in many mechanisms and technical devices. Any turbulent flows are accompanied by velocity pulsations, thus causing vibrations of structural elements, which, in turn, exert an influence on the intensity of heat-transfer processes. The experience in utilization of steam generators shows that, owing to the existing hydrodynamic pulsations, a bundle of tubes vibrates with a frequency of 200–500 Hz. These vibrations determine to a considerable extent the operating parameters of steam generators (especially of the evaporation section) [1]. It is noted that in different plants under operating conditions one can observe pressure pulsations of heat-transfer agents from several tens up to hundreds of hertz. Naturally, two types of intensification of heat- and mass-transfer processes are distinguished: intensification owing to natural vibrations generated by the plant itself and that due to artificially initiated vibrations.

The heat- and mass-transfer processes in boiling systems are of a periodic nature. The occurrence and separation of vapor bubbles, the plug flow of two-phase flows in pipes, etc. are vibrational in nature and lead to the generation of periodic pulsations, which, in turn, change the internal characteristics of boiling. The complexity of description of the process of heat and mass transfer with change in the phase state of a working body under static conditions makes it difficult to study the unsteady boiling that is characteristic of the case of vibrations. This explains the small number of works and their inconsistency in explaining the direction of the influence of vibrations on the intensification of boiling. For the present it is only clear that with increase in the intensity of vaporization the influence of external and internal actions decreases and the contribution of vibration actions can be increased just by increasing their energy (the frequency and amplitude of vibrations).

As a rule, in considering problems of heat and mass transfer and the hydrodynamics of boiling of liquids, the boiling is idealizedly subdivided into a number of simple processes, including the superheat of a liquid by the quantity ΔT, the formation of bubbles, their growth, disappearance, separation, and their motion

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in a liquid. To calculate the heat flux q taken off by a boiling liquid, one also determines the frequency of occurrence of vapor bubbles on the heating surface f, the density of nucleation sites n, and so on.

Vibrations and Boiling Systems. In [1], it is shown that boiling with vibrations applied can be subdivided into coupled vibrational systems, which in the general case represent growing collapsing bubbles, and a vapor-liquid layer capable of executing elastic vibrations. Under certain conditions, the resonance phenomena which favor the occurrence and disappearance of vapor bubbles are implemented in such systems. The presence of sound (acoustic) vibrations leads to a substantial (by an order of magnitude or more) ease of the conditions of *formation of a vapor phase in metastable liquids.* This can be explained by the decrease in the sound (acoustic) wave of an activation barrier to vapor-bubble formation and by the activation of boiling centers on a solid wall. Therefore, under conditions of vibration actions and pressure pulsations, the heat flux and the initial superheats for the start of liquid boiling decrease, while at small heat loads the ordinary convective heat transfer can pass to a boiling condition. It is known that in the presence of an *ultrasonic field*, the abnormally high values of the rise of liquids in wetted capillaries are implemented [2]. This effect is also observed in the case of low-frequency vibrations; moreover, it has been established that the velocity of rise of a liquid depends on the vibrational frequency and increases with improvement in the wetting properties of the liquid (with increase in the wetting angle). In power apparatuses and physicochemical technologies, the superheat of liquids plays, as a rule, a negative role by decreasing the efficiency of processes and leading to unstable operation of the equipment. Therefore, much attention is paid to possible methods of elimination of superheats, i.e., to initiation of nucleation with the aim of providing an earlier start of boiling. One such method which has been sufficiently studied is the initiation of the start of boiling by ultrasound. Experiments [3] have shown the influence of irradiation with ultrasound on a decrease in the mean lifetime of a superheated liquid. Ermakov et al. have drawn the conclusion that the influence of ultrasound increases the probability of the start of boiling without changing the mechanism of the start of boiling as such. The frequency of vibrations has an effect just in certain narrow resonance regions.

For the first time, a great number of works concerned with investigation of heat transfer of a vibrating heat source have been presented in [4], where it is shown that the value of the heat fluxes removed from a vibrating surface substantially depends on the prehistory of the process and foremost on the presence or absence of boiling on the surface. In the case where the value of the heat fluxes does not correspond to the region of incipient and developed boiling, a successive increase or decrease in the heat loads leads to inverse changes in the thermal conditions in the volume. It has been obtained that as compared to the stationary case, heat transfer undergoes a twofold increase and is more proportional to the amplitude of vibrations and to the frequency of pulsations. The hysteresis phenomenon in passage from convection to boiling under vibration actions has also been detected in studying heat transfer on a surface of small size [5], and a conclusion has been drawn on the action of vibration on a thermal boundary layer: vibration gives rise to jet pulsating flows which favors the thinning of the thermal boundary layer on a cooling surface and growth in the heat-transfer coefficients.

Vibrations and Internal Characteristics of Boiling. Investigations of different authors show convincingly that acoustic vibrations substantially change the *internal characteristics of boiling*, namely, the superheat ΔT, the frequency of occurrence of vapor bubbles f, their separation diameters R_{d}, the density of nucleation sites n, the growth rate of vapor bubbles R, the heat fluxes q, and the heat-transfer coefficient α. All these data are scarce; therefore, we will generalize them for each of the characteristics of boiling.

Quantitative data on the dependence of the *superheats of a liquid* in water boiling on a wire are reported in [6]. The main contribution of this work (which is one of the pioneering works) is the detected considerable effect of the action of vibrations on the boiling process (at frequencies of 75 and 100 Hz) which substantially increases the heat-transfer coefficient (nearly twofold).

A considerable-in-volume contribution to the investigation of heat transfer with vibrations has been made by Navruzov et al. [4, 7–10] on a vibrating horizontal heater. Experiments have confirmed that the vibration of the heater greatly transforms the base temperature of the heat-transfer surface. It has been found that a low-frequency vibration can significantly decrease the temperature of the heating surface, while a high-frequency vibration, on the contrary, can increase it. A conclusion has been drawn that a change of the hydrodynamic state of the vapor-liquid flow above the heat-transfer surface under vibration conditions can cause an abrupt change in the heat-transfer coefficient (from 200 to 300 Hz).

Processing of the experimental data on ΔT of Navruzov et al. in relative form and their representation in the form of the dependence on the frequency of heater vibrations ω has shown that on passage to nucleate boiling ($q = 0.7 \cdot 10^5$ W/m^2) a minimum ΔT (and, consequently, a maximum α) occurs for $\omega < 100$ Hz. For $\omega > 100$ Hz the vibration conditions deteriorate heat transfer $\Delta \bar{T} > 1$. In developed boiling ($q = 0.35 \cdot 10^6$ W/m^2) the heat transfer is observed to deteriorate for $\omega < 100$ Hz.

Values of superheats under conditions of vibrational actions have been obtained in [11] with boiling on the surface of small size and with evaporation of a vibrating inductor with the acceleration 6g. Despite the fact that the liquid volume and the heating surfaces differed from those in [10], the extremum in intensification of boiling heat transfer coincided (40–50 Hz). This can testify to the fact that the acoustic properties of the vaporization process and their interaction with vibrations play a greater role than the volume of a liquid in which boiling occurs. At a minimum ΔT (a maximum α), intensification of heat transfer owing to vibration actions can experience a threefold increase. This is explained by the presence of pulsating flows in the thermal boundary layer as a consequence of alternating pressure pulsations that lead to the disturbance of the equilibrium of vapor nuclei inside the pores of the heating surface. The decrease in the thickness of the thermal boundary layer due to vibration-induced mixing hinders the activation of nucleation sites, which increases ΔT. Obviously, these two opposite factors were responsible for the extremum of ΔT. Another, weaker, factor accomplishing extrema in intensification of vibration actions is the ratio of the dimensions of the inductor and of the working chamber. In the case where their dimensions are close, in addition to the dynamic pressure, an extra static pressure develops in the system, whose value depends on the inductor shape (which provides the possibility of extending the region of control of heat transfer in boiling) [11].

The Navruzov experiments were replicated, in fact, by Zitko and Afgan [12], who boiled water on vertical and horizontal plates under vibration actions of up to 70 Hz and with amplitudes $A = 0\text{–}2 \cdot 10^{-3}$ m at heat loads of $q = 33.7\text{–}54.9 \cdot 10^4$ W/m^2 (at atmospheric pressure). With small amplitudes of vibrations a small heat flux deteriorates heat transfer, but with $A = 1\text{–}2 \cdot 10^{-3}$ m, on the contrary, the vibration effect is the strongest in the case of smaller fluxes (in incipient boiling). At the same time, experience [12] has shown that with increase in the heat fluxes small amplitudes ($\sim 0.5 \cdot 10^{-3}$ m) enhance the action of vibrations up to q_{cr} (which is very important, since the main problem is protection against burnouts for $q \cong q_{\text{cr}}$, and this opens up a promising way through vibrations but with smaller amplitudes). With increase in A the effect is opposite, i.e., for small q it is rather strong but with growth in q (and as q_{cr} is approached) the effect becomes weaker (i.e., here it is not very promising to put off the onset of crisis). If we employ the data of [13], we can compare the heat transfer with vibrations on *horizontal and vertical surfaces*. It has been obtained that thermal resistance on a vertical surface is 20% lower, i.e., vibrations enhance the heat transfer on a horizontal surface to a greater degree than on a vertical surface. Interesting work on the study of boiling in an acoustic field under *microgravity conditions* was carried out recently at the University of Washington [14]. This is an important problem that calls for its solution and practical application to the process of efficient boiling under zero gravity. If we compare the process of vaporization under earthly conditions and under gravitation, we will come across the main problem of the efficiency of heat transfer, i.e., the reliable removal of bubbles from the heating surface. Therefore, under microgravity conditions, the large vapor bubbles gather around a heater, which significantly deteriorates heat transfer. At present, it is recognized that under the action of acoustic waves the removal of bubbles from the heating surface is significantly deteriorated. Experiments [14] have revealed that on the whole the heat transfer in acoustic fields shows improvement, but its efficiency under earthly conditions depends on the position of the heater: if the latter is positioned at the wave antinode, superheats decrease by a factor of 1.5–2.0, but if it is positioned at the wave node, then they decrease by 10–20%. Processing of the experiments of [14] on boiling of an FC-72 liquid in an acoustic field with a frequency of 10.18 kHz (2.6 atm) has confirmed the results of [12]: with increase in the heat fluxes the superheat increases (the heat-transfer coefficient decreases), i.e., the effect of vibrational action decreases.

Similarly, the influence of vibration on the internal characteristics of boiling has been evaluated for the first time by the authors in [15–20]. The main idea was the hypothesis that vibrations exert an influence through the wetting angle θ, which changes as the bubble moves with displacement of the heating surface according to the law $x = A \sin(\omega\tau)$. It has been adopted that the wetting angle θ changes according to the sine law $\theta = \theta_0 + A_\theta \sin(\omega\tau)$; the time interval within one cycle (occurrence of a bubble τ_w and its growth and separation τ_d), i.e., $\tau = \tau_w + \tau_d = 1/f$, is considered. The amplitude of pulsations of the wetting angle A_θ is determined from the geometric relation between the bubble radius R and the radius of the cavity mouth R_{cav} [21]: $R_{cav} = R\cos(\alpha - \theta)$ (α is the cavity vertex half-angle). Expansion of α and θ in a Taylor series (as is usually done with linearization about the point θ_0) using the Prisnyakov formula of superheat [22] with account for the Rohsenow correlation (see [21]) $\Delta T = 2\sigma\cos\theta/(\mathcal{R}\rho'' R_{cav})$ has allowed the following expression for the relative *superheat* ΔT to be obtained:

$$\Delta\bar{T} = \cos\Delta\theta - \tan\theta_0 \sin\Delta\theta\,, \quad \Delta\theta = \frac{A\cos^2(\alpha - \theta_0)}{R_{cav}\sin(\alpha - \theta_0)}\sin(\omega/f)\,.$$

Investigating the function $\overline{\Delta T(\omega)}$ for extremum, the authors obtained the following expression of the frequency of vibrations at the extremum point (within the range of time $\tau = 1/f$):

$$\omega_m = f\left[k\pi - \arcsin\left(\frac{\theta_0}{f}\,\frac{R_{cav}\sin(\alpha - \theta_0)}{\cos^2(\alpha - \theta_0)}\right)\right].$$

Calculations from this formula gave results close to experimental ones, $\omega_m = 45$ Hz.

Experimentally, the influence of vibrations on *the growth rate of bubbles* was investigated in [23, 24]. It has been established that the radius of the equivalent medium of a bubble does not always grow monotonically. This is related to the growth of bubbles in a variable-pressure field rather than to the interaction of the neighboring bubbles. An increase in the vibrational amplitude increases the growth rate of bubbles. Theoretical studies of the behavior of vapor bubbles in a varying pressure field can be found in [25, 26]. Solution of the problem of the growth of a vapor bubble in the volume is reduced to the solution of complicated integro-differential equations and, consequently, an analysis can be made only numerically. Therefore, only abstract numerical calculations without comparison with experimental data are mainly available in the literature. Obviously, the problem of the influence of vibrations on the growth of vapor bubbles still invites further investigation, especially with account for the fact that up to now there is no generally accepted model of bubble growth on the heating surface. Naturally, for a vibrating heating surface an analysis must be based on the model of bubble growth on the heating surface. However, the evaluations of a number of authors [25] make it possible to predict qualitatively the process of bubble growth on a vibrating heating surface or under the action of a periodic pressure field. One might expect that a solution will also be periodic; moreover, the growth rate and the regularities of evolution of a bubble will be determined by the relation between the period of applied vibrations and the modulus of bubble growth [27]. According to the evaluations of the solutions of the problem under consideration, the exponent in the law of bubble growth will be larger than its stationary value, equal to 1/2, i.e., the bubble will evolve more rapidly. If we assume that these features are also retained for vapor bubbles growing on the heating surface, then one might expect that the activity of the boiling process under conditions of pulsations and heater vibrations is higher than in the stationary (without vibrations) case.

In [15], the authors have made the first attempt to evaluate directly the influence of vibrations on a time variation of the bubble radius. If we choose the time τ as the reference moments of comparison of the values of the radius without vibrations R_0 and with vibrations R, then, using the Labuntsov formula $R_0^2 = 4C_0^2\,\mathrm{Ja}\,a'\tau$ and having integrated the expression $dR^2 = 4C^2(\theta)\,\mathrm{Ja}\,a'd\tau$, we can obtain the relative value of the radius for each time:

$$\sigma = \overline{R} = \frac{R}{R_0}\,\frac{1}{C_0^2\tau}\int_0^{\tau}\frac{d\tau}{\sqrt{[1+\cos(\theta_0+A_\theta\sin\omega\tau)]^3\,[2-\cos(\theta_0+A_\theta\sin(\omega\tau))]}}\,.$$

Calculating the integral of this expression and prescribing the time of bubble growth τ, we can compare the influence of vibrations on the growth of vapor bubbles.

Experimental data [28] have demonstrated that the *separation size of bubbles* depends, first of all, on the vibrational amplitude A: with its increase, R_d decreases. Processing of the experimental data of Chekanov and Kul'gina [23] has allowed us to obtain the dependence of the coefficient of the influence of vibrations χ on the vibrational amplitude $\chi = R_d/R_{d0}$. These initial data show that at a vibration frequency of 80 Hz an increase in the vibrational amplitude entails a decrease in the function χ. A comparison of these results to those given above can testify to the inconsistency of the considered influence; therefore, it is necessary to gain experimental information on the influence of the vibrational amplitude and frequency on the separation dimensions of vapor bubbles.

Theoretical evaluation of the influence of vibrations on the separation of vapor bubbles on a vibrating heating surface has been presented for the first time by the authors in [15]. Consideration has been given to the simplest case of the action of three forces on a vapor bubble, namely, the Archimedean force P_g, the surface cohesive force P_σ, and the resistance (or hydrodynamic) force R_c. The condition of equilibrium of the three forces leads to a cubic equation for the bubble-separation radius R_d, which can be substantially simplified for the case $\dot{R} \ll \dot{x}$, and a solution for R_d leads to the following ratio of the bubble-separation size with vibrations R_d and without vibrations R_{d0}:

$$\chi = \frac{R_d}{R_{d0}} = \sqrt{\frac{\cos\Delta\theta + \mathrm{ctan}\,\theta_0\sin\Delta\theta}{1 - A\omega^2\sin(\omega/f)/g}}\,.$$

As is seen, the simplest scheme of separation yields a rather complicated algebraic dependence. Naturally, extension of the experiment, a set of statistics on the separation size, and use of other, more exact separation models will allow refinement of the function χ.

The *frequency of separation of vapor bubbles* from a vibrating heating surface depends on resonance phenomena which are determined by the relation between the vibrational frequency and the frequency of separation of bubbles as well as by the acoustic parameters of a reservoir with a liquid. Therefore, experimental studies must encompass a wide spectrum of vibrational frequencies and amplitudes. At present, a great amount of data on f under vibration conditions is available.

The authors [15] have analyzed the experimental data of Kul'gina on the frequency of occurrence of vapor bubbles f under vibration conditions: with increase in the vibrational amplitude A and frequency ω, the frequency of occurrence of bubbles f decreases substantially (by a factor of two); moreover, the influence of the amplitude A becomes more pronounced by decreasing the vibration frequency ω by a heater. The authors [15] suggest accounting for the influence of vibrations on f by introducing a certain function φ that represents the ratio of the mean frequencies of bubble separation under vibration conditions f and without vibrations: $\varphi = f/f_0$. In [5], it has been established that the action of an occasional frequency on single nucleation sites does not cause a substantial change in the frequency f. However, in the case of applying vibrations with a frequency equal to the frequency of bubble separation f, the effect of the action turns out to be substantial. Experimental results [24] have demonstrated that in the case of the coincidence of the two frequencies the frequency of bubble separation f decreases. In this case, the larger the acceleration of a vibration source and the stronger the mixing of a liquid in the near-wall layer, the stronger the influence of vibration on f.

Theoretically, the influence of vibrations on the frequency of occurrence of bubbles has been evaluated in [15] on the basis of the theoretical formula [21]

$$\bar{f} = f/f_* = \frac{4}{\pi}\left(\frac{\mathrm{Pe}_*}{\mathrm{Ja}}\right)^2 \left[1 + \frac{1}{\pi c^2 \phi^2}\left(\frac{\bar{R}_{\mathrm{d}}\,\mathrm{Pe}_*}{\mathrm{Ja}^2}\right)^2\right]^{-1} .$$

If the frequencies on motionless and vibrating heaters are computed under the same thermohydrodynamic conditions ($\mathrm{Pe}_* = \mathrm{const}$; $\mathrm{Ja} = \mathrm{const}$), the function $\varphi = f/f_0$ will have the rather complicated form

$$\varphi \cong \frac{\pi c_0^2\,\phi_0^2 + (\bar{R}_{\mathrm{d}}\,\mathrm{Pe}_*/\mathrm{Ja}^2)^2}{\pi c^2 \phi^2 + (\bar{R}_{\mathrm{d}}\,\mathrm{Pe}_*/\mathrm{Ja}^2)^2} ,$$

where

$$\phi^2 = 1 + 2\left(\frac{c_1}{c}\right)^2 \mathrm{Ja} + 2\,\frac{c_1}{c}\sqrt{(1 + (c_1/c)^2\,\mathrm{Ja})\,\mathrm{Ja}}\ ; \quad c_1 = \sqrt{\frac{3}{4\pi}}\,\sin^2\theta/(1 + \cos\theta)^2\,(2 - \cos\theta) .$$

As is seen, theoretical evaluation of the influence of vibrations on the frequency of bubble separation represents a rather complicated problem that calls for additional investigations.

Experiments on the *density of nucleation sites* are rather complicated, and in the literature there are no data pertaining to the conditions of vibration actions. Therefore, for this internal characteristic of boiling it is especially important to have theoretical evaluations of the influence of heater vibrations on n. The relative density of nucleation site $\bar{n} = n/n_{\max}$ is determined by the formula [29] $\bar{n} = \exp(-3.1\bar{h})/(b\bar{h}^{\nu})$, where $\bar{h} = h/h_{\mathrm{m}}$ is the ratio of surface microirregularities (running and root-mean square); $n_{\max}$ is the maximum density of nucleation sites (with the onset of crisis); $n_{\max} = \eta_1/R_{\mathrm{d1}}^2$, R_{d1} is the separation diameter with saturation of the boiling crisis, i.e., $R_{\mathrm{d1}} = f(\Delta T_{\mathrm{1cr}}) = f(\mathrm{Ja}_{\mathrm{1cr}})$. Proceeding from these arguments, it is easy to establish that the vibrational field influences the density of nucleation sites in terms of the separation size of a vapor bubble at the moment of saturation of the boiling crisis, i.e., $\nu = n/n_0 = \chi^2$. Obviously, the problem of the influence of vibrations on the density of nucleation sites calls for its refinement.

Vibrations and Heat Transfer in Boiling. The majority of experimental studies contain the closing stage of *heat transfer*, i.e., determination of the dependence of the heat-transfer coefficient α or taken-off heat fluxes q on the temperature difference ΔT for varied frequencies ω and amplitudes A of actions. Correspondingly, we will consider an analysis of the experimental dependences $\alpha(\Delta T)$, $\alpha(q)$, and $q(\Delta T)$ separately.

One of the pioneering works, in which the *heat-transfer coefficient* under ultrasonic vibrations of a heater with boiling of degassed distilled water with subcooling has been found to increase is [24]. The authors have noted that, depending on the liquid temperature, the heat-transfer coefficient can increase by 5–30%. A 13% increase in the heat-transfer coefficient was also obtained in the experiments in [30] with tubes of small size ($d = 18$ mm) in the case of vibrations with an amplitude of 1.2 mm and a frequency of up to 1450 Hz. In [5], Antonenko et al. have investigated the influence of vibrations on the heat-transfer rate in developed and film boiling on a rough surface of small size with application of vibrations with a frequency of 15 sec^{-1} and acceleration of 59 $\mathrm{m/sec}^2$ for different positions of the vibrator. It has been established that with increase in the density of the heat flux, the intensifying influence of vibrations on heat transfer decreases and in the case of developed boiling it can decrease substantially. Antonenko et al. explain this by the fact that under developed boiling vapor bubbles block the heat-releasing surface and thus prevent mixing of the liquid volume in the near-wall layer. Moreover, the two-phase layer near the heating surface and the vapor bubbles represent dampers absorbing the energy of vibrations. It has been noted that the position of a vibration source relative to the heating surface practically does not influence the mode of change of α (vibrations ±5%). Antonenko et al. [5] have drawn the conclusion that the vibration of the liquid volume most strongly influences the intensity of heat transfer in the initial and final stages of boiling, while in their experiments the developed boiling is not amenable to intensification by the suggested method. The influence of the vibrational amplitude A of a heater and of the vibrational frequency ω on the heat-transfer coefficient α in boiling of ethyl alcohol and a 25% aqueous solution of it was investigated by Zitko and Afgan [31]. The results of our processing of their experiments in the form of the dependence of $\bar{\alpha}$ on the amplitude A for different vibrational frequencies has shown that in the mixtures the action of vibration is larger by approximately a factor of two than in a pure substance; moreover, its magnitude changes from 15 to 63% as compared to the heat transfer without vibrations. In another work of these authors [12], the influence of the heat flux on the increase in the heat-transfer coefficient in boiling with vibrations is considered. It has been obtained that for a horizontal surface there is a tendency toward a decrease in the influence of vibrations on α, while for a vertical surface the effect remains practically constant. Interesting results on the dependence of α on ΔT in acoustic fields for different points of the position of the heater, i.e., at the antinode of the wave or at its node, have been obtained in FC-72 boiling on the earth and under microgravity conditions [14]. For the antinode, α exceeds the heat-transfer coefficient at the node by more than a factor of two and it is several times higher than the heat-transfer coefficient in boiling without applying an acoustic field. Ingenious results were obtained by S. Bondarenko and colleagues (a private communication) at the Dnepropetrovsk State University in investigation of heat transfer under conditions of the action of mechanical low-frequency vibrations in water and sugar syrup for frequencies of up to 150 Hz and amplitudes of from 0.5 to 5 mm. The author has carried out a series of experiments and revealed the regimes in which the heat-transfer coefficient increased by an order of magnitude. It has been obtained that a decrease in the absolute pressure in the system increases α as well. The main goal of the work of S. Bondarenko was to find the ways of improving the efficiency of the processes in the food industry, in particular, in sugar crystallization. The author has shown the influence of the interrelation between frequency and amplitude on the increase in mixing of a liquid and in α. The optimum values of the coefficient α at a certain frequency ω_{opt} exceed α without vibrations by a factor of 2.5 and even of 9.

Representation of heat transfer in the form of a *Nukiyama curve*, i.e., in the form of the dependence of the heat fluxes q on the temperature difference $\Delta T = T_w - T_s$, is characteristic of work carried out at the Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine under the supervision of one of the authors [7, 8, 10, 28]. In [7], the form of the dependence $q \sim \Delta T^m$ is analyzed. For low values of the heat fluxes ($< 2 \cdot 10^5$ W/m^2), ethanol boiling with heating has $m \approx 3.3$, while for high values of q ($> 3 \cdot 10^5$ W/m^2) $m \approx 9$. On the average, $m = 3.6$ within the entire range of operating parameters. The frequency of vibration actions, low or high, causes approximately the same change in the law of heat transfer, with $m = 2.4$–2.8. It has been obtained that high-frequency vibrations lead to greater intensification of heat transfer. Under the conditions of developed boiling ($q > 3 \cdot 10^5$ W/m^2), the influence of vibration depends on the frequency of vibration actions: for low frequencies, $m = 5.7$ and for high frequencies, $m = 1.8$. In [15], an analysis is made of these results and a method is suggested for evaluation of the influence of the vibrational frequency on the heat fluxes. Indeed, if we use the theoretical formula for calculation of heat transfer in boiling [21] $\text{Pe}_* = (4/3)\bar{n}fR_d^3$, then substitution of the relations obtained above into this dependence yields $\text{Pe}_* = (4/3)\bar{n}\varphi\chi^3\text{Pe}_{*0}$. Whence we obtain $\text{Pe}_*/\text{Pe}_{*0} = q/q_0 = \eta = \varphi\chi^5$, i.e., the vibrational frequency influences the heat fluxes through the separation size of bubbles $\bar{R}_d$ (to the fifth power!) and through the frequency of occurrence of these bubbles.

Conclusions. The *action of vibrations* on heat- and mass-transfer processes in a certain range of frequencies and amplitudes can lead to a *considerable increase* (*up to ten times*) *or decrease in the heat-transfer coefficient*. Therefore, this trend of investigations is rather promising from both the applied and scientific viewpoints and must include determination of the optimum operating conditions, creation of special vibrational devices, and search for promising spheres of application of vibrations.

NOTATION

A, vibrational amplitude; A_θ, amplitude of pulsations of the wetting angle; a, thermal diffusivity; C, proportionality coefficient in the law of bubble growth according to the scheme of Labuntsov; c, proportionality coefficient in the law of bubble growth according to the general scheme (see [21]); f, frequency of the occurrence of vapor bubbles on the heating surface, $\mathrm{g} = 9.8$ m/sec^2; $\bar{h} = h/h_\mathrm{m}$; m, exponent; n, density of the nucleation sites; P, force; P_g, Archimedean force; P_σ, surface cohesive force; P_c, resistance force (or hydrodynamic force); q, heat flux taken off by a boiling liquid; q_cr, critical heat fluxes; $R = 2c\phi\mathrm{Ja}\sqrt{a'\tau}$, bubble radius; $\dot{R}$, growth rate of vapor bubbles; T, temperature; ΔT, superheat of the liquid; x, coordinate; α, heat-transfer coefficient; cavity vertex half-angle; $\varphi = f/f_0$; $\chi = R_\mathrm{d}/R_\mathrm{d0}$; $\nu = n/n_0 = \chi^2$; $\eta = \varphi\chi^5$; θ, wetting angle; ρ, density; σ, surface tension; τ, time; ω, vibrational frequency; $\mathcal{R}$, gas constant; $\mathfrak{J}$, evaporation heat; Ja, Jacobi number; Pe, Péclet number; $\mathrm{Pe}_* = qR_*/(\mathfrak{J}p''a')$, modified Péclet number with the characteristic dimension $\mathrm{R}_* = \sqrt{\sigma/q(\rho' - \rho'')}$. Subscripts: cav, cavity mouth; m, extremum parameters; root-mean-square; s, saturation; w, parameters on the wall; expectation time; 0, parameters without the action of vibrations; d, separation from the surface; cr, critical parameters; 1, parameters of the first crisis (burnout); $'$, liquid parameters; $''$, vapor parameters.

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