acoustic effects in a liquid during boiling and bubbling are the result of pressure pulses, which promote different states of the bubble-formation process. The bursts of damped acoustic oscillations in a liquid are the result of the action of a single pressure pulse.

NOTATION

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

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

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

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

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

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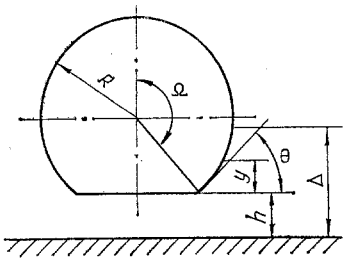

Fig. 1. Theoretical model: vapor bubble in equilibrium with a liquid microlayer on a solid substrate.

pressure $P(h) = Ch^{-n}$, and by its surface tension $\omega = \frac{C}{n-1} h^{-n+1} + \sigma$. The so-called "angle of contact" is determined by the equation $\cos\Theta = \sigma/\omega$. Since the available experimental data in the literature concerning adsorption films relate only to a very narrow range of their existence and do not permit a quantitative analysis of the regularities of the boiling process, we present below a quantitative evaluation of the properties of the microlayer by processing information on the kinetics of bubble growth on the surface of a solid.

The present analysis repeats methodologically Labuntsov's work [9].

The theoretical model is complemented by a microfilm determining the shape of the bubble and the conditions of heat exchange (see Fig. 1). Instead of the measured averaged temperature head wall–vapor we use its instantaneous value in accordance with the method of [4-6]. We examine a vapor bubble growing on the surface of a solid semiinfinite body with uniform initial temperature. The bubble is separated from the solid surface by a quasiequilibrium adsorption film.

With the growth of the bubble, the vapor pressure and the splitting pressure of the layer decrease, and the thickness h of the film increases. Evaporation proceeds both from the plane and from the spherical surface of the bubble immersed in the temperature gradient layer. The heat-exchange equation may be written in the form

$$r\rho'' \frac{dV}{d\tau} = \int_s q\,ds. \tag{1}$$

The right-hand side may be interpreted in the following manner:

$$\int_s q\,ds = (T_п - T_s)\left[\frac{\lambda_2}{h}\pi R^2(1-\cos^2\Omega) + 2\int_h^\Delta \pi R \frac{dy}{(h+y)/\lambda_2}\right].$$

After substitution $R = \frac{2\sigma}{C} h^n$; $\cos\Omega = \dfrac{\sigma}{\frac{C}{n-1}h^{1-n} + \sigma}$ [8] and after integration

$$\int_s q\,ds = (T_п - T_s)\,\pi\frac{2\sigma}{C}\left\{\lambda_2\frac{2\sigma}{C}\left[h^{2n-1} - \frac{\sigma^2 h^{4n-3}}{\left(\frac{C}{n-1} + \sigma h^{n-1}\right)^2}\right] + 2\lambda_2 h^n \ln\frac{h+\Delta}{2h}\right\}$$

we transform (1) into

$$d\tau = r\rho'' dV \Big/ \left[(T_п - T_s)\,\pi\frac{2\sigma}{C}\left\{\lambda_2\frac{2\sigma}{C}\left[h^{2n-1} - \frac{\sigma^2 h^{4n-3}}{\left(\frac{C}{n-1} + \sigma h^{n-1}\right)^2}\right] + 2\lambda_2 h^n \ln\frac{h+\Delta}{2h}\right\}\right]. \tag{2}$$

This equation cannot be integrated immediately. An approximate solution is obtained when the law of the mean is used: the denominator on the right-hand side of the equation is averaged with respect to h. This enables us to determine the temperature head $(T_П - T_s)$ with the aid of the solution of Carslow and Jäger, approximated in [5] by the relation

$$T_п - T_s = \frac{T - T_s}{1 + \sqrt{\frac{2}{3}\pi\left(\frac{\lambda_2}{\lambda_1}\right)^2 \frac{a_1\tau}{\delta^2}}}, \tag{3}$$

δ is in our case the mean film thickness for the given bubble radius.

TABLE 1. Parameters of the Growth of a Vapor Bubble on a Steel Substrate with Water Pressure P = 1.013 bar

R, m	h, m	cos Θ	ω, N/m	$P(h)$, N/m	a	$T-T_s$, K	$T_П-T_s$, K	τ_e, sec	τ_p, sec
$1\cdot10^{-4}$	$2{,}27\cdot10^{-7}$	0,773	$7{,}615\cdot10^{-2}$	1118					
$3{,}49\cdot10^{-4}$	10^{-6}	0,7785	$7{,}56\cdot10^{-2}$	337	145	20	5,81	$3{,}5\cdot10^{-4}$	$3{,}5\cdot10^{-4}$
$5{,}34\cdot10^{-4}$	$1{,}5\cdot10^{-4}$	0,78	$7{,}546\cdot10^{-2}$	220	96,5		5,38	$8{,}7\cdot10^{-4}$	$8{,}7\cdot10^{-4}$
$7.9\cdot10^{-4}$	$2{,}15\cdot10^{-6}$	0,798	$7{,}376\cdot10^{-2}$	149	64,3		4,8	$2{,}6\cdot10^{-3}$	$2{,}54\cdot10^{-3}$
$1\cdot10^{-3}$	$2{,}75\cdot10^{-6}$	0,782	$7{,}526\cdot10^{-2}$	118	52,4		4,25	$5\cdot10^{-3}$	$5\cdot10^{-3}$

If we substitute (3) into (2) and integrate, we obtain the solution

$$2\left[\frac{\sqrt{\tau}}{a}-\frac{1}{a^2}\ln\left(1+a\sqrt{\tau}\right)\right]_{\tau_0}^{\tau}=\frac{r\rho''(h-h_0)}{\pi\frac{2\sigma}{C}(T-T_s)}\left\{\left|\frac{1}{3}\left(\frac{2\sigma}{C}\right)^3h^{3n}(2-3\cos\Omega+\cos^3\Omega)\right|_{h_0}^{h}\right\}\Big/\left\{\left|\frac{2\sigma}{C}\lambda_2\left[\frac{h^{2n}}{2n}-\right.\right.\right.$$

$$\left.\left.\left.-\frac{\sigma^2h^{4n-2}}{(4n-2)\left(\frac{C}{n-1}+\sigma\delta^{n-1}\right)^2}\right]+2\lambda_2\frac{h^{n+1}}{n+1}\left[\ln\Delta-\ln2-\ln h+\frac{1}{n-1}\right|_{h_0}^{h}\right\},$$

where

$$a=\sqrt{\frac{2}{3}\pi\left(\frac{\lambda_2}{\lambda_1}\right)^2\frac{a_1}{\delta^2}}.$$

The object of the calculation is to determine the characteristic of the adsorption layer, i.e., the values of C and n corresponding to the experimentally measured growth rates of the bubbles. Thereby we also find the initial temperature gradient ($T-T_s$) and the instantaneous temperature heads wall–vapor ($T_П - T_s$). The constants C and n are chosen on the basis of the conditions of equilibrium between the bubbles and the microlayer, matched with the experimental data on the kinetics of bubble growth.

All the theoretical values are chosen and corrected in the process of calculating several experimental points of the curve $\tau = f(R)$, until complete coincidence is attained. In the investigations we used the experimental data of [10]. The constants in the equations of splitting pressure and of surface tension of the layer thus determined were $C = 2.54\cdot10^{-4}$ and $n = 1.02$. The calculated values of ($T - T_s$) and ($T_П - T_s$) are given in Table 1.

NOTATION

C, n, constants; σ, ω, surface tension of the liquid bulk and of the layer; $T_П$, surface temperature; T_s, saturation temperature; T, initial wall temperature; λ_1, λ_2, thermal conductivity of the metal and of the microlayer, respectively; a_1, thermal diffusivity of the metal of the wall; τ_e, experimentally determined time of bubble growth; τ_p, calculated time of bubble growth.

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HEAT EXCHANGE IN BOILING OF THERMOLABILE SUSPENSIONS

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Results are presented from an experimental study of boiling of a sugar crystal suspension in an intercrystalline solution under conditions of free motion and reduced pressure.

The intensity of heat transfer to boiling suspensions consisting of sugar crystals in an intercrystalline solution (massecuite) is described by more complex laws than the boiling of single-component systems. The amount of heat transfer to the massecuite is significantly lower than to the sugar solution or solute (water), and other conditions being equal, is dependent on the content of dry materials, thermal flux intensity, pressure, and thermophysical and boiling regime factors. The low value of α_2 is related to the fact that massecuites are thermolabile suspensions, and the heat-exchange process in vacuum crystallizers occurs at reduced pressures and low q values.

At the present time a significant number of studies have been published on heat transfer and the vapor formation mechanism for unary and binary liquids and solutions of organic and inorganic origin, but such data do not provide a complete physical picture of the boiling of suspensions, and do not allow calculation of α_2 in the design of vacuum crystallizers. For this purpose, the experimental equipment described in [1, 2] was used to obtain data under quasistationary conditions on the boiling of stable and metastable massecuites with concentrations DM_m = 73.6-92.4%, CR = 10-50%, p = 5.2-68.4 kPa, q = 2-100 kW/m^2. The pressure in each experiment was maintained constant, as were the parameters of the massecuite, while the thermal flux was varied, causing changes in α_2. The dependence of α_2 on q obtained in this manner was not single-valued, indicating the existence of different heat exchange regimes — convective, and undeveloped and developed bubble boiling. Since in convective heat exchange and undeveloped bubble boiling α_2 is very unstable, the limits for commencement of developed bubble boiling were determined, these values indicating that with increase in the number of crystals in the massecuite the time for commencement of developed boiling is retarded, although the material in a layer adjacent to the wall is superheated by tens of degrees. This can be explained by an increase in effective viscosity, which leads to a decrease in the mobility of the massecuite mass. With increase in solid phase content the turbulization of the wall layer decreases, so that small vapor bubbles cannot overcome the increased hydrostatic pressure and their sphere of influence decreases in size.

The curves shown in Fig. 1 permit determination of the limits of thermal flux regulation during the massecuite cooking period for optimum use of energy resources at a given pressure over the material. The figure shows that the more stable heat and mass transfer region lies in the area above a line indicating a specific sugar crystal content in the massecuite.

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