EXPERIMENTAL AND THEORETICAL STUDY OF THE TRANSIENT BOILING MECHANISM

V. V. Kostyuk, I. I. Berlin,
and A. V. Karpyshev

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The heat-transfer mechanism in the transition boiling region is studied theoretically and experimentally.

Transition boiling is of interest from both the purely scientific (since it is a little studied region of high-intensity heat exchange with a complex phase interaction mechanism) and the practical viewpoints (since it is realized in a large number of cryogenic, power generation and metallurgical equipment, for stabilization of superconductors and in failure regimes in atomic reactors). Studies of temperature pulsations in the walls, which characterize heat transfer in the transition region, were performed in [1-4]. However, in a number of cases contradictory data were obtained. Attempts to generalize the characteristics of the physical mechanism and complete mathematical models describing the process are unknown to the authors.

Experimental and theoretical studies of the heat-exchange mechanism were thus carried out for transition boiling of a liquid on a planar surface.

The theoretical analysis rests on the following concepts concerning the physical mechanism of the phenomenon. At high values of wall temperature T_W the liquid is separated from the heating surface by a vapor film (region of stable film boiling). With decrease in T_W the vapor film becomes ever thinner, so that development of oscillations in the phase boundary can lead to contact of the liquid with the heating surface. At the point of contact with the hot wall the liquid is heated, and upon attaining a certain superheating stable nuclei of the vapor phase develop in the liquid layer adjacent to the wall. The vapor bubbles then grow, merge together into a continuous film, and carry liquid off from the heating surface. The film thus formed proves to be hydrodynamically unstable, leading to the appearance of alternating liquid contact with the wall; and the process is repeated cyclically.

As the wall temperature is decreased, the length of the period of contact between liquid and heating surface increases, and the intensity of heat liberation in the transition boiling region increases from the low values characteristic of film boiling to the high values characteristic of bubble boiling. With further reduction in surface temperature the number of vapor nuclei formed decreases to a point where the growing vapor bubbles reach breakaway diameter before they merge together and the transition regime is replaced by stable bubble boiling.

In the transition boiling regime the mean heat-transfer intensity over time on each section of the heating surface depends on the mean duration of its contact with the liquid and vapor phases of the boiling medium and on the characteristics of heat exchange at each stage of the cyclical process. A theory of transition boiling developed on the basis of the physical mechanism presented above will include mathematical models of three processes which define the appearance and termination of liquid contact with the heating surface: 1) development of hydrodynamic instability in the vapor–liquid phase boundary; 2) heating of the liquid at its point of contact with the heating surface; 3) development and growth of vapor bubbles until their merger into a continuous film.

Hydrodynamic instability of the vapor film was analyzed for the case of film boiling of a semiinfinite layer of liquid on a planar heating surface located at an arbitrary angle γ to the horizontal. The analysis was based on the classical Rayleigh formulation of the problem, supplemented by consideration of heat exchange, phase transition on the interphase boundary, and the oscillatory process of thermal conductivity in the wall. It was assumed that the mean motion of the phases and heat exchange could be described by a one-dimensional

model, allowing determination of the mean values over time of the vapor film thickness δ, the rate of removal of evaporating mass from the phase boundary v_{ev}, and the mean mass velocity of vapor motion along the heating surface u_v. A periodic low-amplitude perturbation is superposed on this mean motion. The characteristics of the process can be represented as the sum of average and pulsation components (the film thickness $\delta = \bar{\delta} + \tilde{\delta}$, the longitudinal velocity component $u = \bar{u} + \tilde{u}$, etc.).

The problem reduces to solution of a system of equations including the continuity equation, the equations of motion for the vapor and liquid, and the thermal conductivity equation for the wall. The dependence of the complex oscillation frequency ω on the wave numbers k_x and $k = \sqrt{k_x^2 + k_z^2}$ was obtained [5]:

$$\frac{\dfrac{\rho_1}{\rho_v}\,\omega^2 + \dfrac{\rho_1 - \rho_v}{\rho_v}\,g\cos\gamma k - \dfrac{\sigma}{\rho_v}\,k^3}{(\omega - u_v k_x)\,\mathrm{cth}\,(k\delta) - ikv_{ev}} + (\omega - u_v k_x) =$$

$$= \frac{\lambda_w \sqrt{k^2 - \dfrac{i\omega}{a_w}}\,\dfrac{1}{\rho_v r}\,\dfrac{\partial q_w}{\partial \delta}}{\lambda_w \sqrt{k^2 - \dfrac{i\omega}{a_w}} + \dfrac{\partial q_w}{\partial T_w}}.$$

(1)

The possibility of tangency of the liquid to the heating surface is defined by the development of the dominant wave, for which the amplitude increment coefficient β (imaginary component of the circular frequency ω) takes on its highest value:

$$\beta_d = \sup_{k_x, k_z} I_m(\omega).$$

(2)

The expressions obtained indicate that for a saturated liquid the effect of heat exchanges on oscillation of the vapor film is negligibly small, while increase in undercooling increases the stability of the phase boundary (although with decrease in wall thermal conductivity the effect of this factor is attenuated). Other stabilizing factors are surface tension and viscosity, while slippage of the vapor relative to the liquid is destabilizing. The force of gravity causes an increase in oscillations in boiling on heating surfaces directed downward.

Liquid heating at the point of contact with the wall was analyzed by calculating the temperature field developed after contact of a semiinfinite layer of liquid with initial temperature T_{1o} and a two-layer plate with initial temperature T_w. The system of differential equations for thermal conductivity of the main wall material, coating, and liquid was solved. It follows from the solution obtained that the most significant factors determining heating of the liquid near the wall are the coating thickness and the thermal activity coefficient $\varepsilon = \sqrt{\rho c \lambda}$ of the liquid and coating.

The duration of the first stage of liquid contact with the wall (heating of the liquid by thermal conductivity) was determined from the condition of achieving the superheating necessary for formation of stable vapor nuclei (Fig. 1):

$$t_{tr} = \frac{\sigma^2 T_s^2 (1 + \cos\theta)^2}{\rho_v^2 r^2 \Delta T_b^2 a_1}\, f\!\left(\frac{\Delta T_v}{\Delta T_b}\right).$$

(3)

To analyze the process of growth and merger of vapor bubbles, use was made of empirical relationships known from the theory of bubble boiling for the surface density of vapor formation centers and the bubble growth rate [6, 7]. From the condition of bubble merger (filling the entire heating surface), the duration of the second stage of liquid contact with the wall was determined (from appearance of vapor nuclei to formation of a continuous vapor film):

$$t_m = \frac{\sigma^2 T_s^2}{\rho_v^2 r^2 \Delta T_b^2 a_1 \mathrm{Ja}^2}\, f_1\!\left(\frac{\rho_1 c_{p1} \Delta T_v}{\rho_v r}\right).$$

(4)

By comparing the periods required for growth of bubbles to the breakaway radius t_{br} and for
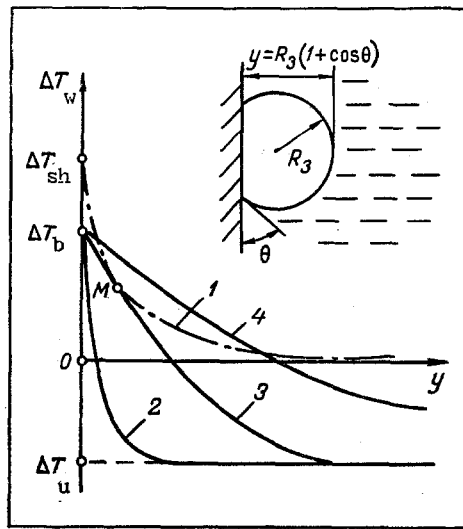
Fig. 1. Determination of minimum
duration of liquid heating before
formation of vapor nuclei: 1)
liquid superheat required for for-
mation of vapor nuclei of minimum
radius for given temperature head;
2, 3, 4) temperature field in liquid
at contact with superheated wall for
various times (2, $t < t_m$; 3, $t = t_m$;
4, $t > t_m$).

bubble merger t_m for the case of boiling of a saturated liquid on a horizontal heating surface
we obtain an expression defining the temperature head of the point of departure from stable
bubble boiling:

$$\Delta T_{DNB} = C \, (\rho_v r g)^{1/7} \, (\sigma T_s)^{3/7} \, \varepsilon_1^{-4/7}. \tag{5}$$

The mathematical model of heat exchange in transient boiling considered three basic phy-
sical mechanisms which follow each other serially on every portion of the heating surface:

heating of a thin layer of liquid at its point of contact with the wall due to thermal
conductivity until the formation of stable vapor nuclei;

a mechanism similar to bubble boiling during the period of bubble growth until their
merger into a continuous film:

a mechanism similar to film boiling during the period of vapor insulation of the heating
surface, until development of hydrodynamic instability in the phase boundary causes the next
contact of the film with the wall.

Representation of the mean thermal flux density in transient boiling as the sum of three
components with consideration of the fraction of time spent in each process:

$$q_{tr} = (q_n t_n + q_b \, t_m + q_f t_v)/(t_{tr} + t_m + t_v) \tag{6}$$

allows us to obtain an expression for boiling on a thick thermally conductive surface

$$q_{tr} = \frac{\alpha_f k_v \Delta T_w^2 + 2\varepsilon_1 \, \sqrt{k_n/\pi} + \alpha_b \, k_m \Delta T_w^{-3}}{k_v \Delta T_w + k_n \Delta T_w^{-2} + k_m \Delta T_w^{-4}}, \tag{7}$$

where

$$k_n = \frac{\sigma^2 \, (1 + \cos\theta)^2 \, T_s^2}{a_1 \, \rho_{vs}^2 \, r^2} \left(1 + k_u \, \frac{\Delta T_u}{\Delta T_b} \right) k_1; \tag{8}$$

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$$k_{\mathrm{m}} = \frac{\sigma^2 T_s^2}{\varepsilon_\ell^2} \left(1 + k_{\mathrm{u}}' \frac{\rho \ell c \rho \ell \Delta T_{\mathrm{u}}}{\rho_v r} \right) k_2; \tag{9}$$

$$k_{\mathrm{v}} = \frac{c_{\mathrm{pv}}}{\beta_{\mathrm{d}} r} \left(1 + k_{\mathrm{u}}'' \frac{\rho \ell c_{\mathrm{p}} \ell \Delta T_{\mathrm{u}}}{\rho_v r} \right)^{-1} k_3. \tag{10}$$

For boiling on thin or poorly thermally conductive walls the function $q = f(\Delta T_w)$ is more complex in character. In this case with increase in the ratio $(\rho c \lambda)_1/(\rho c \lambda)_w$ the curve of transition boiling shifts to the region of higher temperature heads.

The theoretical model described contains three empirical constants k_1, k_2, k_3, related to the random character of vapor formation centers on the heating surface, the time of vapor nucleus formation, and the initial perturbation of the vapor film surface.

In experimental studies of transient boiling the mean durations of contact of the liquid and vapor phases with the wall were chosen as the quantitative characteristics of the physical mechanism. These values were determined experimentally using the fact that during the period of wall contact with liquid there is an inensification of heat exchange and sharp drop in wall temperature, while during the period of vapor contact the wall temperature increases.

Wall temperature oscillations were measured with Chromel—Copel thermocouples with lead diameter of 0.1 mm, with the working junction installed flush with the heating surface. The thermocouples were installed in drillholes in the working section, eliminating distortion of the heat-exchange pattern directly above the surface area studied.

The experimental apparatus included a chamber 8 liters in volume, provided with a liquid temperature stabilization system (accurate to ±0.5°K). Boiling was carried out on the face of a copper cylinder 20 mm in diameter, connected to a massive heat storage block, which was heated by thermal radiation from an electrical furnace. The thermal flux density was calculated from indications of a differential thermocouple with junctions installed at distances of 5 and 10 mm from the heating surface. The experimental setup was maintained in the steady state by controlling the flow of an auxilary heating agent, gaseous nitrogen pumped through drillings in the specimen.

The boiling of water, ethanol, and freon-113 was studied. Liquid undercooling was varied over the following ranges: water $\Delta T_u = 0$–24°K; ethanol $\Delta T_u = 0$–18°K; freon-113 $\Delta T_u = 0$–54°K. The mean height of heating surface microroughness for the various specimens was $R_a = 0.54$, 1.4, 4.1, and 6.4 μm. The effect of surface orientation was studied for two positions: vertical and horizontal. The mean calculated uncertainties in measurements of the parameters defining the process did not exceed the following values: heating surface temperature $\delta T_w = \pm 0.7$°K: thermal flux density $\delta q = \pm 10.8\%$: period of phase contact with the heating surface $\delta t = \pm 0.6$ msec.

The following results were obtained in visual studies of transition boiling. For heat exchange to the saturated liquid the presence of a quite thick (4–6 mm) vapor film, apparently "torn through" to the liquid surface at individual points, was characteristic. With increase in temperature head the area occupied by these gaps decreases, and at the second critical point a continuous stable vapor film is established. With increase in ΔT_w the thickness of the vapor film in the transition boiling regime gradually decreases. At sufficient liquid undercoolings ($\Delta T_u = 10$°K for water, $\Delta T_u = 15$°K for ethanol, and $\Delta T_u = 30$°K for freon) areas appear on the heating surface which are coated with a large quantity of fine (of the order of 0.2–0.5 mm) vapor films which overlap each other and give an overall mat appearance. This process generates a high intensity sound of an explosive character. Further increase in undercooling leads to an expansion of the areas where such heat exchange occurs. The acoustical effects then intensify significantly. With increase in undercooling the mean thickness of the unstable vapor film decreases, which fact we ascribe to intensified condensation of the vapor phase. In the region of the second boiling crisis there appears on the specimen surface relatively large (10–20 mm^2) vapor films, the size and number of which increase with approach to ΔT_{cr2}.

Change in heating surface roughness leads to no qualitative change in the process over the entire ΔT_w range of the transitional boiling range. However, when the surface orientation is changed from horizontal to vertical, there is a marked inhomogeneity in the process. Even at the first crisis point there is a well-expressed vapor film on the upper portion of the
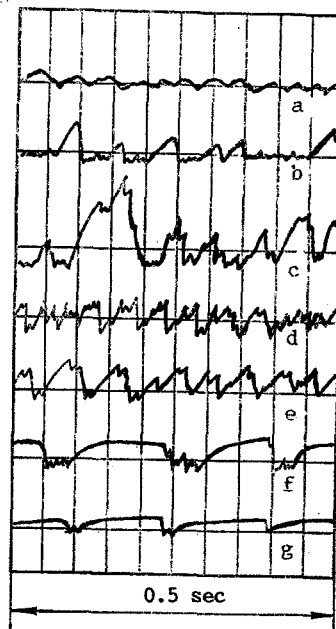
Fig. 2. Typical recordings of heating surface temperature oscillations (copper, water, $\Delta T_u = 6°K$):
a) $T_W = 15°K$; b) 22; c) 31; d) 61; e) 88; f) 97; g) 112°K.

heating surface, while developed bubble boiling takes place in the lower area. With increase in temperature head the vapor film gradually expands over the entire surface. However, while for a horizontal orientation the probability of appearance of "gaps" in the film is identical for any point on the surface, for vertical orientation the "gaps" are found more often in the lower region. Increase in undercooling of the liquid, as for horizontal orientation, leads to appearance of a finely dispersed vapor structure, but only in the lower region, the upper being covered by a vapor film for the entire temperature head range studied. Such results are apparently explainable by the differing conditions existing for removal of the vapor phase with horizontal and vertical orientation of the heating surface.

Analysis of thermograms obtained during the experimental studies showed that the character of heating surface temperature oscillations depends on the temperature head and the liquid undercooling (Fig. 2).

In the bubble boiling region the oscillation frequency is 20-40 Hz, which corresponds to the frequency of vapor bubble breakaway. At thermal flux densities of 70-80% of q_{crl} flares appear in the surface temperature, the amplitudes of which are 5-10 times the mean level characteristic of stable bubble boiling (Fig. 2b). The abrupt temperature increase is caused by formation of a dry region on the heating surface due to merger of several "dry" sections which develop under growing vapor bubbles due to evaporation of a portion of the microlayer, while the subsequent abrupt drop is caused by filling of this region by liquid with reestablishment of bubble boiling. Transition boiling near ΔT_{crl} is characterized by similar temperature oscillations: immediately after an abrupt drop there is a period with low amplitude (Fig. 2c). Thus the physical mechanisms of the process are the same in the precrisis bubble boiling regime and the adjacent transitional boiling region and the passage of the boiling curve through a maximum with increase in temperature head ΔT_W is a consequence of the gradual decrease in the fraction of time over which the wall is wetted by liquid.

With further increase in ΔT_W the segments characteristic of bubble boiling disappear and are replaced by quite stable wall temperature oscillations: an abrupt drop and abrupt increase (Fig. 2d). This character of T_W oscillations indicates the presents of two components of heat exchange during the period of liquid contact with the wall: nonsteady state heating (the rapid temperature drop) and bubble boiling (period with small oscillations). Moreover, it is evident that the contribution of the second component decreases with increase
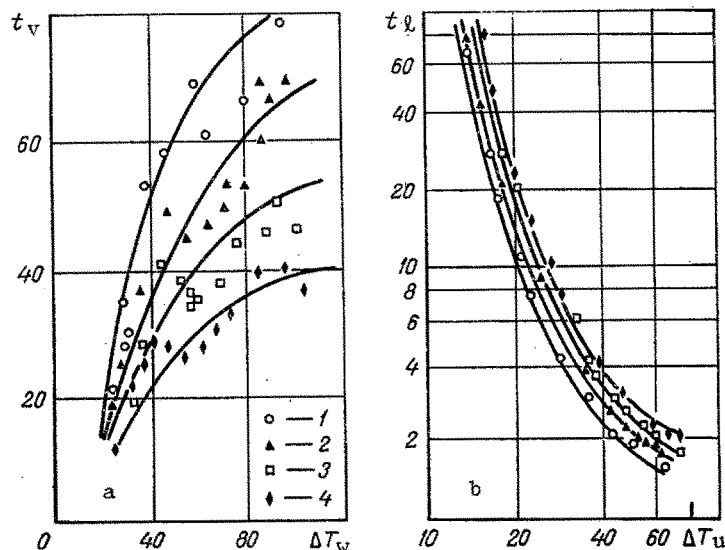
Fig. 3. Effect of temperature head and liquid subcooling on transition boiling mechanism characteristics (copper, ethanol). a) Mean duration of liquid contact with wall; b) mean duration of existence of vapor phase (1, $\Delta T_u = 0°K$; 2) 6, 3) 12; 4) 18). t_v, t_l, msec; ΔT_w, °K.

in temperature head. Increased liquid undercooling shifts the boundary of the transitional boiling zone in which temperature pulsations typical of bubble boiling are observed into the region of higher temperature heads. At wall superheating close to ΔT_{cr2} the oscillograms begin to show abrupt temperature flares (Fig. 2f, e) related to the appearance of relatively large vapor films.

The time-averaged characteristics of the mechanism involved in transitional boiling of ethanol (average duration of liquid contact t_l and vapor contact t_v with the wall) are shown in head. The corresponding curves for water and freon-113 are similar in form. As ΔT_u is increased the mean duration of liquid existence on the heating surface increases and t_v decreases. The dependence of oscillation frequency on temperature head has a clearly expressed maximum in the middle portion of the transition boiling region, which shifts toward higher temperature heads with increase in liquid undercooling. The duration of liquid contact with the wall t_l decreases with increase in ΔT_w, being equal to 1-3 msec in the region of the second crisis. For a saturated liquid the time of existence of the vapor film t_v increases rapidly with increase in ΔT_w, but even an insignificant increase in undercooling produces an abrupt decrease in this boiling characteristic.

The effect of undercooling on the characteristics of the boiling mechanism can be explained by vapor condensation in the upper portions of vapor formations and increase in the time required for nonsteady state heating of the liquid to the point where vapor nuclei develop. It is interesting that the relative liquid contact time with the wall $t_l=t_l/t_l+t_v$ at the first crisis point is practically independent of the parameters defining the process ΔT_u, R_a, and depends only slightly on the physical properties of the liquid. For water $\bar{t}_{l\,cr1} = 0.72$, for ethanol $\bar{t}_{l.cr1} = 0.6$, for freon-113 $\bar{t}_{l\,cr1} = 0.7$.

With decrease in the height of heating surface microroughness near ΔT_{cr1} there is some increase in q_{tr} for a given temperature head, due to a decrease in the number of vapor formation centers on the surface. The effect of surface roughness decreases with approach to ΔT_{cr2}. There is practically no change in the frequency of liquid contact with the wall upon reduction in R_a.

Experiments on a vertical surface recorded an increase in the oscillation frequency f by a factor of 1.5-2 times (for a given ΔT_w). The mean period of liquid contact with the wall changed only slightly.

The behavior of the experimental curves $t_l = \varphi(\Delta T_w)$ confirms the physical model proposed. The duration of liquid contact with the wall t_l falls abruptly in the low temperature head
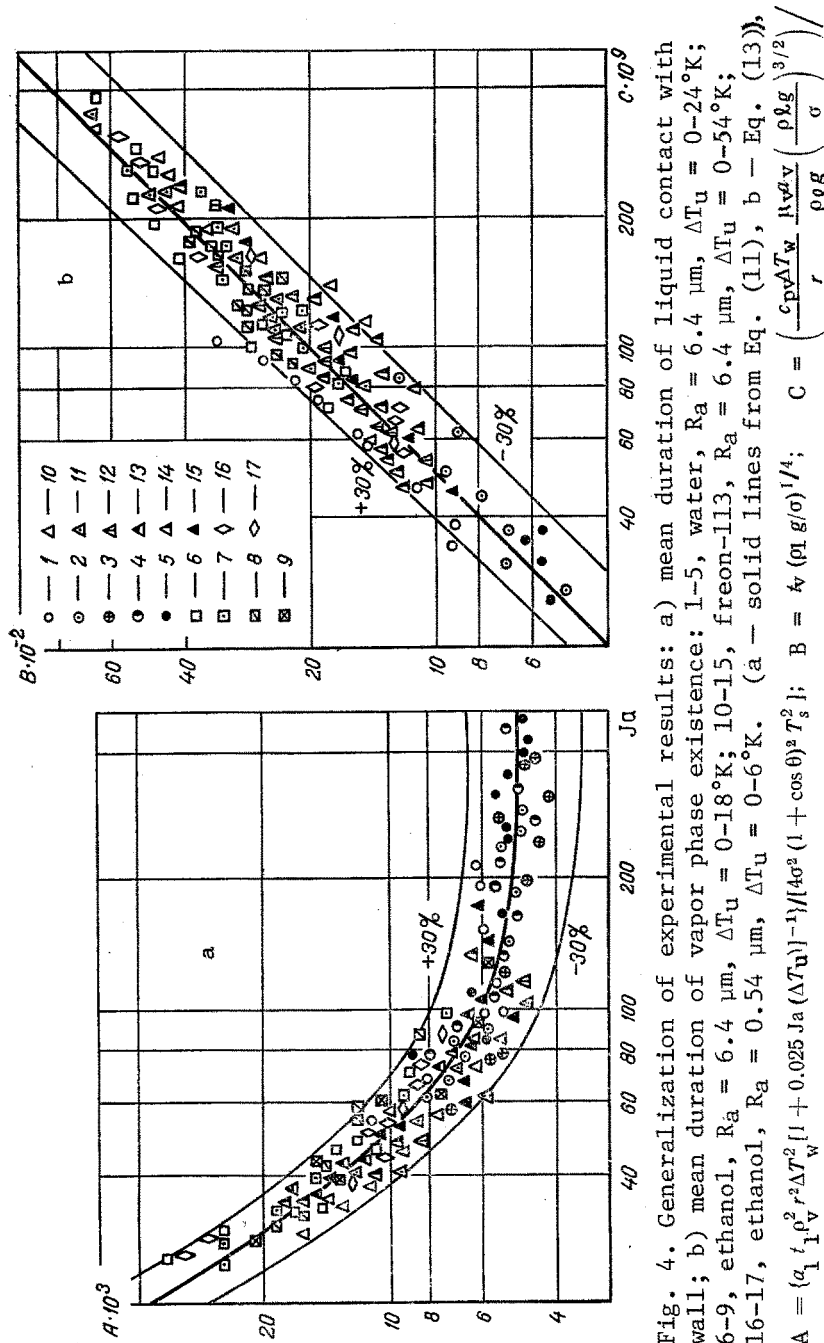
Fig. 4. Generalization of experimental results: a) mean duration of liquid contact with wall; b) mean duration of vapor phase existence: 1–5, water, Ra = 6.4 μm, ΔT_u = 0–24°K; 6–9, ethanol, Ra = 6.4 μm, ΔT_u = 0–18°K; 10–15, freon-113, Ra = 6.4 μm, ΔT_u = 0–54°K; 16–17, ethanol, Ra = 0.54 μm, ΔT_u = 0–6°K. (a — solid lines from Eq. (11), b — Eq. (13)),

$$A = \{a_1 t_1 \rho_v^2 r^2 \Delta T_w^2 [1 + 0.025 \, Ja \, (\Delta T_u)]^{-1}\} / [4\sigma^2 (1 + \cos\theta)^2 T_s^2]; \quad B = t_v (\rho_l \, g/\sigma)^{1/4}; \quad C = \left(\frac{c_p v \Delta T_w}{r} \frac{R v a v}{\rho_l g} \left(\frac{\rho_l g}{\sigma} \right)^{3/2} \right) /$$

$$(1 + 0.04 \, Ja \, (\Delta T_u)).$$

range, $t_\ell \sim \Delta T_w^{-4}$, and slows with increase in ΔT_w (rate of fall), $t_1 \sim \Delta T_w^{-2}$.. This behavior can be explained by the fact that at low ΔT_w the major part of the contact time is spent in growth and merger of bubbles (the duration of this process $t_m \sim \Delta T_w^{-4}$),, while at high temperatures it is spent in heating the liquid by thermal conductivity $(t_r \sim \Delta T_w^{-2})$.. These facts permit generalization of the experimental data on mean duration of liquid contact with the wall (Fig. 4a) with the dimensionless expression

$$\frac{a_1 \, t_1 \, {}_{\circ} v^2 r^2 \Delta T_w^2}{4\sigma^2 (1 + \cos\theta)^2 \, T_s^2} = \left(490 + \frac{1{,}34 \cdot 10^6}{Ja^2}\right)\left(1 + 0{,}025 \frac{\rho_\ell \, c_p \, \ell \Delta T_u}{\rho_v r}\right) \tag{11}$$

with an accuracy of $\pm 30\%$ (with variation of t_ℓ by two orders of magnitude). For the components t_{tr}, t_m we have the ratio

$$t_{tr}/t_m = 0{,}37 \cdot 10^{-3} \, Ja^2. \tag{12}$$

The experimental data on duration of the heating surface contact with the vapor phase can be generalized with an accuracy of $\pm 30\%$ by the dimensionless expression (Fig. 4b)

$$t_v \left(\frac{\rho_\ell g^3}{\sigma}\right)^{1/4} = 21 \cdot 10^6 \frac{c_{pv} \Delta T_w}{r} \frac{\mu_v a_v}{\rho_\ell g l_0^3} \left(1 + 0{,}04 \frac{\rho_\ell c_{pv} \Delta T_u}{\rho_v r}\right)^{-1}, \tag{13}$$

where

$$l_0 = \sqrt{\sigma/\rho_\ell g}.$$

Equations (10), (13) are applicable to transition boiling in a large volume on horizontal highly thermally conductive heating surfaces with a technical roughness $R_a = 0.54$-6.4 μm for liquids thermodynamically similar to water, ethanol, and freon-113.

NOTATION

T, absolute temperature, °K; u, v, velocity, m/sec; δ film thickness m; β, amplitude increment; g, acceleration of gravity, m/sec^2; γ, angle of surface orientation, rad; θ, wetting angle, rad; λ, thermal conductivity coefficient, W/m·K; c, specific heat, J/kg·K; ρ, density, kg/m^3; r, heat of evaporation, J/kg; a, thermal diffusivity coefficient, m/sec^2; q, thermal flux density, W/m^2; σ, surface tension coefficient, N/m; t, time, sec; μ, dynamic viscosity coefficient, Pa·sec; $\Delta T_w = T_w - T_s$, temperature head, °K; ΔT_u, $= T_s - T_1$, liquid undercooling with respect to saturaion temperature, K; Ja, Jacob number. Subscripts: 0, initial; w, wall; ℓ, liquid; v, vapor; p, at constant pressure; s, on saturation line; u, undercooled; tr, transient; m, merger; cr, critical; b, boundary; d, dominant.

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