10. J. W. Beams, Phys. Fluids, 2, No. 1, 1-4 (1959).
11. C. A. Angell and H. Kanno, Science (Washington), 193, No. 4258, 1121-1122 (1976).
12. P. G. Debenedetti and M. C. D'Antonio, J. Chem. Phys., 84, No. 6, 3339-3345 (1986).
13. N. Macmillan, Atomistics of Failure [Russian translation], Moscow (1987), pp. 35-103.
14. A. D. Izotov and V. B. Lazarev, Dokl. Akad. Nauk SSSR, 305, No. 5, 1155-1159 (1989).
15. G. V. Berezhkova, Filamentary Crystals [in Russian], Moscow (1969).
16. M. M. Martynyuk, Zh. Fiz. Khim., 57, No. 4, 810-821 (1983).
17. A. D. Kirshenbaum, J. A. Cahill, P. J. McGonigal, and A. V. Grosse, J. Inorg. Nucl. Chem., 57, No. 10, 1287-1298 (1962).
18. S. J. Henderson and R. J. Speedy, J. Phys. Chem., 91, No. 11, 3069-3072 (1987).
19. V. P. Skripov and M. Z. Faizullin, High Temp. High Pres., 18, 1-12 (1986).
20. N. M. Bogdanov, V. P. Koverda, and V. P. Skripov, Fiz. Khim. Stekl., 6, No. 4, 395-400 (1980).

CRITICAL BOILING HEAT TRANSFER: SPECIAL CASE OF SMOOTH EXCHANGE OF BUBBLE AND FILM BOILING REGIMES

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UDC 536.423.1

The author presents results of an unconventional analysis of critical heat transfer interpreted as boundaries of a transition boiling region with a smooth exchange of bubble and film boiling regimes. A stepwise exchange of these boiling regimes, i.e., critical heat transfer in the textbook sense, is examined as a special case. The influence of various parameters on the boundaries and the transition boiling zone is demonstrated.

For a better understanding of critical boiling heat transfer one should examine the question unconventionally. Then we shall see that one would not then consider critical boiling heat transfer as a sharp exchange of types of boiling. In the variation of wall temperature there is a smooth transition from pure bubble boiling to pure film boiling via a large boiling transition zone, extensive with respect to T_w, in which these two types interchange continuously, both in time and over the surface. Therefore, it would be more correct to speak of conditions (boundaries) for starting and stopping the transition boiling regime.

Then the usual concept of critical bubble boiling on a low thermal inertia surface as a breakdown as the heat input increases and as a stepwise transition to a remote region of film boiling can be considered as a special case of the usually smooth transition process.

As a special case of the general transition process it is also convenient to treat the hydrodynamic theories of critical bubble and film boiling, considering stepwise transitions from bubble boiling to film boiling and back as a consequence of perturbing the hydrodynamic stability of these processes. In critical bubble boiling heat transfer one considers conditions for stepwise separation of the liquid from the wall, and the creation of a complex vapor film, and in critical film boiling one considers conditions perturbing the vapor film and the establishment of bubble boiling over the entire surface.

In our opinion, it is much more general to study the mechanism and the physical processes of the transition boiling and the causes of its occurrence within the bubble and film boiling regimes.

In replacing bubble boiling by transition boiling with an increase of T_w an important matter will be the appearance and the comparatively long persistence of dry spots, i.e.,

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K. E. Tsiolkovskii Moscow Institute of Aviation Technology. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 59, No. 3, pp. 437-445, September, 1990. Original article submitted January 30, 1990.

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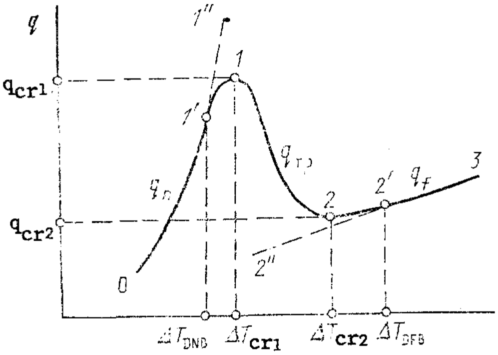

Fig. 1

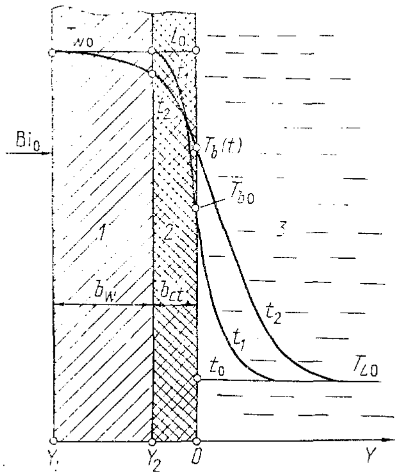

Fig. 2

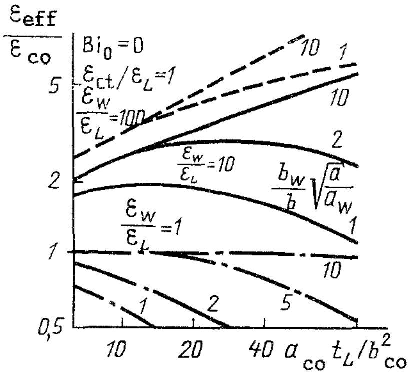

Fig. 3

Fig. 1. Boiling curve [2]: 0-1') stable bubble boiling; 1'-2') transition boiling region; 2'-3) region of stable film boiling.

Fig. 2. Temperature field in the zone of contact of the liquid with a two-layer heater surface [2]: 1) wall; c) coating; 3) liquid.

Fig. 3. Nomogram for determining the effective thermal activity of a two-layer wall [2].

zones of film boiling in which the liquid cannot contact the wall for thermodynamic reasons, since the temperature at the boundary between the wall and the liquid T_b exceeds the limiting superheat temperature T_{lim} of the liquid. On the other hand, replacement of film boiling by transition boiling begins when conditions arise briefly for contact of the liquid with the wall (oscillations of the surface film and $T_b < T_{lim}$ at points of contact of the wall with the liquid).

The occurrence of such conditions has been examined in recent years as thermodynamic critical boiling episodes, which are encountered in actual processes much more frequently than are hydrodynamic critical boiling events.

In the general case, as we shall show below, critical boiling or, more exactly, the occurrence of transition boiling is governed by a combination of hydrodynamic and thermodynamic conditions.

To understand better the processes at the boundaries of the transition boiling region we consider processes in transition boiling.

In transition boiling each point of the heat transfer surface f is alternately in contact with the liquid and with the vapor and at any specific time a part of the surface

f_L is in contact with the liquid, and a part f_V is in contact with the vapor. It is evident that at a boundary with bubble boiling (point 1 on the boiling curve, Fig. 1) $f_V = 0$, $F_L/f = 1$, and at the boundary with film boiling (point 2' in Fig. 1), on the other hand, $f_L = 0$ and $f_V/f = 1$.

According to the data of our and other experiments, at the point 1' we have $q_{1'} = 0.86\, q_{cr1}$, $\Delta T_{1'}/\Delta T_{cr1} = 0.78$, $f_L/f = 0.8$, and at the point 2 we have $f_L/f = 0.04$, $\Delta T_{cr1} \simeq \Delta T_{cr2}$. It is interesting that these relations hold when many factors act on transition boiling.

In general, in transition boiling the heat-transfer intensity and the region of thermal superheating of the wall $\Delta T_W = T_W - T_S$, where it occurs, is determined by a combination of hydrodynamic and thermodynamic conditions, and the possibility and frequency of contact of the liquid with the wall.

The time of contact of liquid with the wall t_L at each point is determined by two processes.

When a liquid with temperature T_{L0} comes in contact with the wall at temperature T_{W0}, an intermediate temperature is established on the surface (in a one-dimensional analysis)

$$T_{b0} = T_{L0} + (T_{w0} - T_{L0})/(1 - \varepsilon_L/\varepsilon_w), \tag{1}$$

where $\varepsilon = \sqrt{\rho c \lambda}$ is the thermal activity of the medium.

Thereafter there begins the process of unsteady heating of the liquid layer by heat conduction and cooling of the wall. This process continues until time t_T, when the superheated liquid layer causes the onset and growth of vapor bubbles.

We evaluate the time t_T required to generate and begin the growth of vapor centers by the expression:

$$t_{\text{T}} = \frac{\sigma^2 T_s^2 (1 + \cos\theta)^2}{\rho_v^2 r^2 \Delta T_b^2 a_L \,\mathrm{Ja}^2}\, F \frac{\Delta T_s}{\Delta T_b}. \tag{2}$$

Bubble growth proceeds until they coalesce at time t_{co}, when contact of the liquid with the wall is disrupted and film boiling occurs, which lasts for a certain time t_V.

We evaluate the bubble growth time until coalescence by the expression

$$t_{co} = \frac{\sigma^2 T_s^2}{\rho_v^2 r^2 \Delta T_b a_L \,\mathrm{Ja}^2}\, F \frac{\rho_L c_{pL} \Delta T_s}{\rho_v r}, \tag{3}$$

where the Jacob number is $\mathrm{Ja} = \rho_L c_{pL} \Delta T_W / \rho_V r$.

By comparison with the experimental data in [2] we obtained the following dimensionless expressions for evaluating t_T, t_{co}, t_V:

$$\frac{1}{4} a_L t_{\text{T}} \left[\frac{\rho_{vs} t \Delta T_w}{\sigma (1 + \cos\theta) T_s} \right]^2 = 490 \left(1 + 0.025 \frac{\rho_L c_{pL} \Delta T_s}{\rho_{vs} r} \right), \tag{4}$$

$$\frac{1}{4} a_L t_{co} \left[\frac{\rho_{vs} r \Delta T_w}{\sigma (1 + \cos\theta)\, T_s} \right]^2 = \frac{1.34 \cdot 10^6}{\mathrm{Ja}^2} \left(1 + 0.025 \frac{\rho_L c_{pL} \Delta T_s}{\rho_{vs} r} \right), \tag{5}$$

$$t_v \left(\frac{\rho_L g^3}{\sigma} \right)^{1/4} = 21 \cdot 10^6 \frac{c_{pv} \Delta T_w \mu_v a_v}{r \rho_L g l_0^3} \left(1 + 0.04 \frac{\rho_L c_{pL} \Delta T_s}{\rho_{vs} r} \right). \tag{6}$$

From these it can be seen that t_T and t_{co} increase as ΔT decreases, while t_V increases.

But with a thin enough wall, or when thin coatings are applied to the wall, or there are deposits, encrustation or contamination, the value of $\Delta T_W = \Delta T_b$ can change during the contact.

The interface temperature T_b is given by Eq. (1) and is constant only if $t_T \leq b_n^2/4\, a_n$, where b_{ct} is the thickness of the coating and a_{ct} is its thermal diffusivity. In the opposite case (Fig. 2) the thermal signal successfully penetrates the coating and reaches the main wall material at time $t_1 = b_{ct}^2/4a_{ct}$, and the interior wall surface at time $t_2 = (b_{ct}^2/4a_{ct}) \cdot [1 - (b_{ct}/b_W)\sqrt{a_W/a_{ct}}]^2$, leading to a temperature rise at the place of contact. Therefore to use Eq. (1) we introduce the concept of effective thermal activity of the two-layer wall ε_{eff}, which one finds from the nomogram shown in Fig. 3 [2].

It is evident that leakage of heat along the wall to the place of contact can also influence the temperature at its boundary.

From what has been said, it becomes clear how one can control the unsteady processes of transition boiling and the transition boiling itself by varying the wall material, its coating and thickness, i.e., ε_{eff}, the underheat of the liquid ΔT_s, its thermophysical properties, the wetting angle, the pressure, the surface roughness, the spatial orientation of the boiling surface, the liquid hydrodynamics, etc.

The quantitative nature of these variations is shown in Figs. 4-10, according to the experimental data of various authors. In interpreting these experimental data we especially examine the influence of the different parameters on displacement of the boundary of the transition boiling region q_w, ΔT_w, and on the unsteady aspects of these phenomena.

As a boundary between film and transition boiling we shall take the point 2' in Fig. 1, in which, due to the thermodynamic and the hydrodynamic conditions, there arise such a number of contacts of the liquid with the wall that the heat transfer to these becomes appreciable, and the boiling curve begins, with a decrease of ΔT_W, to deviate from the film boiling law toward greater values of q_w.

As we increase the area of contact, or the relative time of contact of the wall with the liquid, the boiling curve passes through a minimum (at point 2, Fig. 1), which is usually stated to be critical film boiling (q_{cr2}, ΔT_{cr2}), although here there is already 4-5% of the area in contact with the liquid.

Analogously to this process, the exchange of bubble boiling with transition boiling begins when, due to the hydrodynamic and thermodynamic conditions, there appears such a number of "dry" (coated with vapor) sections of the heater surface that the reduced heat transfer there leads to deviation (at point 1' of Fig. 1) with increase of ΔT_w of the boiling curve from the developed bubble boiling curve. Due to further increase of the surface coated with vapor the boiling curve will pass through a maximum (point 1 of Fig. 1), which is usually taken as critical bubble boiling (q_{cr1}, ΔT_{cr1}). In fact, this point already lies quite far into the transition boiling zone. Here already about 15-20% of the area is in contact with vapor.

Usually to the left of point 1' the central part of the surface under a growing bubble dries out or divides into a number of growing bubbles. The removal of heat by vapor from this part is difficult, and its temperature begins to increase the faster (for a given heat release), the thinner is the wall (or the less its heat capacity), and the worse is the heat leakage to the adjoining regions wetted with liquid. If the temperature of a dry spot exceeds that at which subsequent contact with the liquid becomes impossible, following separation of a bubble, then this place becomes dry, as long as its temperature is not reduced due to leakage and removal of heat.

Experiments have shown that this time in the region $q_{1'} < q_w < q_{cr1}$ can exceed the bubble growth time by a factor of 10 or more.

Numerical solution of problems of unsteady heat conduction for a dry spot [3] has confirmed what has been said, and has shown that for small Fourier numbers $Fo = a_w t_m / R_m^2$ (R_m is the maximum radius of a dry spot, t_m is the time to reach it, and a_w is the thermal diffusivity of the wall material) the heat removal from a dry spot by heat conduction is small.

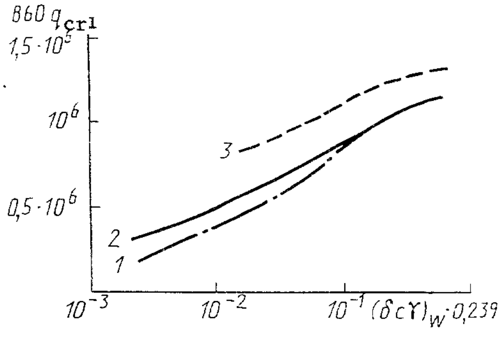

Fig. 4. Dependence of q_{cr1} for water on the heat capacity of the wall material per unit area [1]: 1) heating with variable current; 2) heating with constant current; 3) with an oxide film present. $860 q_{cr1}$, kW/m^2; $(\delta c \gamma)_w \cdot 0.239$ $kW \cdot sec/(m^2 \cdot K)$.

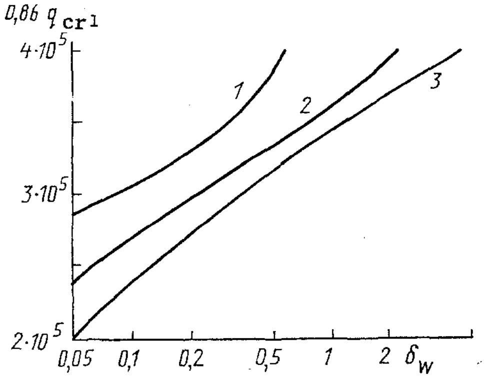

Fig. 5

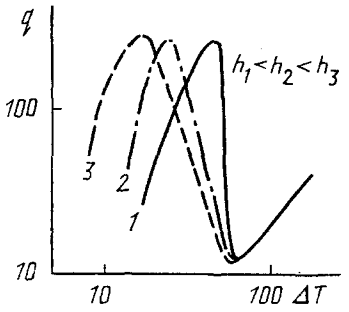

Fig. 6

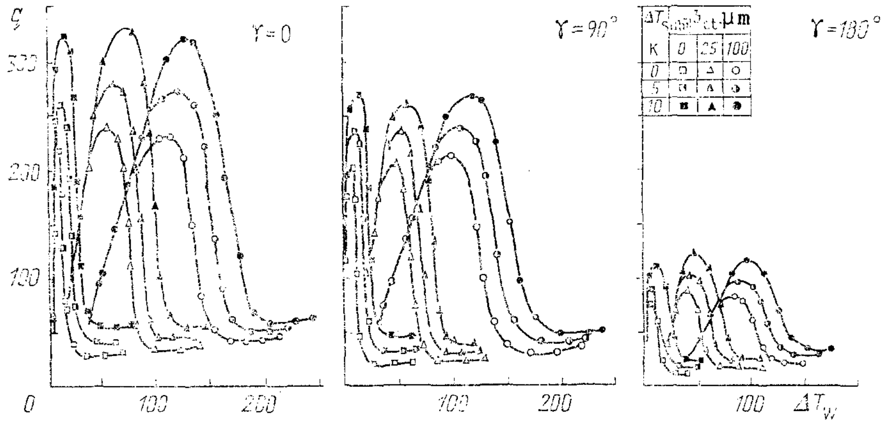

Fig. 7

Fig. 5. Dependence of q_{cr1} for n-propanol on the thickness and the material of the heater: 1) copper; 2) steel; 3) inconel. We have $0.86q_{cr}$, W/m^2; δ_w, mm.

Fig. 6. Influence of the height of surface roughness of the heater h on the boiling curve of n-pentane on a copper surface [4]. We have q, kW·m^{-2}; ΔT, K.

Fig. 7. Influence of the underheat ΔT_s, the heater surface spatial orientation γ°, and the thickness of the low-conductivity coating on the boiling curve of nitrogen on a plate of size 390 × 150 mm [2]. The quantity ΔT_w is in K.

The rate of increase of wall temperature in a spot is determined by $b_w c\rho$ and the heat release. Evidently, for each wall material and t_m there is a value of b_w^* for which further increase of $b_w \geq b_w^*$ will not influence q_{cr1}, if we neglect the increasing role here of heat leakage along the wall.

If there are poorly conducting coatings of oxide films on the surface of the dry spot, then liquid contact with the dry spot can occur at higher values of T_w than on a clean wall, due to the causes described above.

What has been said is confirmed in Fig. 4 [3], from which one can see that q_{cr1} is proportional to the parameters $b_w\rho c/\tau_m$, $\varepsilon_L/\varepsilon_w$, and the dependence on the type of current.

Figure 5 [3] illustrates the role of heat leakage along the thickness of the material and its thermal conductivity.

To improve our understanding of the causes of displacement of the boundaries of the transition boiling region we shall examine how various parameters influence this.

It can be seen from Fig. 6 [4] that an increase of the roughness, which does not influence film boiling nor its critical value, moves the rest of the boiling curve to the left, toward smaller ΔT_w. In the transition boiling region this is due to formation of a large number of vapor-generating centers and to a decrease, for a given ΔT_w, of the time of contact t_L with the liquid.

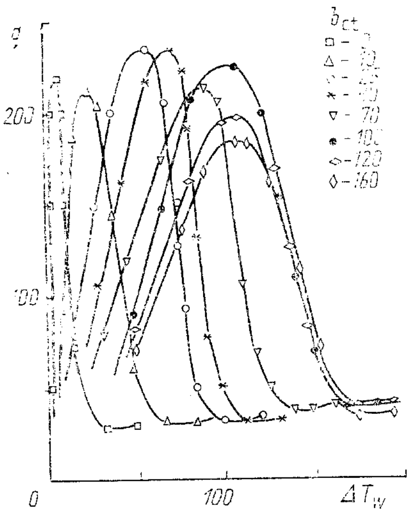

Fig. 8

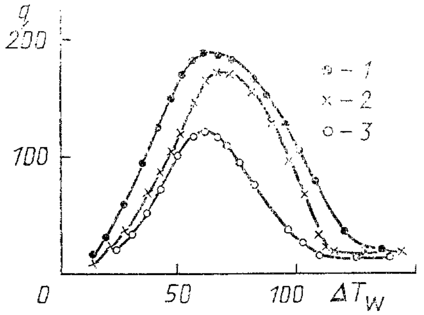

Fig. 9

Fig. 8. Influence of a low-conductance coating on the boiling curve of saturated nitrogen on a horizontal disk [2]. b_w, μ.

Fig. 9. Influence of the rate of unsteady cooling of tubes with fluoroethylene coatings (b_p = 40 μ) on the boiling curves in a large volume of saturated nitrogen [1]: 1) δ_w = 2 mm; 2) 1; 3) 0.5. q, kW/m^2.

An increase of the wetting angle θ, as can be seen from the formula for computing the critical film boiling

$$\frac{\Delta T_{\mathrm{cr}2}}{T_{\mathrm{cr}} - T_L} = \left[0.16 + 2.5\sqrt{\frac{\varepsilon_L}{\varepsilon_w}} + \left(\frac{\varepsilon_L}{\varepsilon_w}\right)^2\right](1 + 0.13\cos\gamma)\frac{1 - \cos\theta}{2}, \tag{7}$$

moves the entire transition boiling region to the left, since it decreases the area of contact of liquid with the wall.

All the regions of the boiling curve depend appreciably on the combination of hydrodynamic and thermodynamic conditions, which is confirmed especially clearly by Fig. 7 [2]. From Fig. 7 it can be seen that with a change of the orientation of the boiling surface, i.e., with a substantial change of hydrodynamics, the qualitative nature of the influence of liquid underheat and the conditions of unsteady heat transfer from the surface are maintained, while the quantitative characteristics of the boiling curves change considerably.

A certain degree of worsening of conditions of vapor removal from the wall, a decrease and change of the nature of instability of the vapor film as the heater surface is rotated from $\gamma = 0$ to $\gamma = 90°$ lead to decrease of the values (q_1, $\Delta T_{1'}$), ($q_{\mathrm{cr}1}$, $\Delta T_{\mathrm{cr}1}$), and ($q_{\mathrm{cr}2}$, $\Delta T_{\mathrm{cr}2}$), i.e., to displacement of the boiling curves to the left and decrease of q_w in the transition boiling region.

This trend is especially marked for $\gamma = 180°$, i.e., the boiling surfaces point downward. This is a case where the vapor film is stable in the film boiling region and it is difficult to evacuate vapor to the bubble boiling region. Here it is important to note that in these conditions the mechanism for generation and development of transition boiling is maintained, but the hydrodynamics present substantial constraints, making it difficult to break down the vapor film.

It is interesting to note the role of the underheat, which has practically no influence on the development of bubble boiling (not counting the expansion of its region in the direction of increase of ΔT_w due to the unsteady effects of bubble boiling), while it strongly influences transition boiling. This is a clear illustration of the fact that critical boiling is only the boundary of transition boiling, and these boundaries lie in fact at points 1' and 2' of the boiling curve (see Fig. 1).

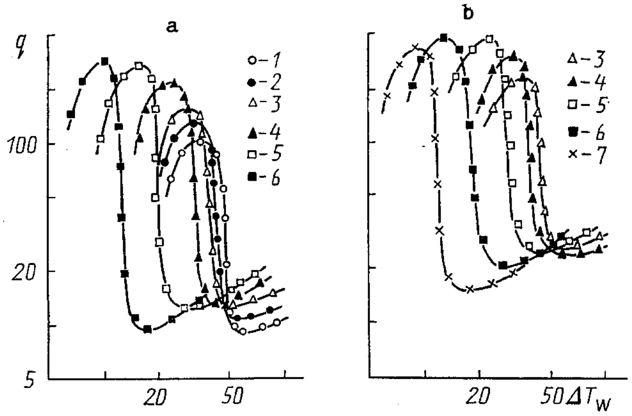

Fig. 10. Influence of pressure in transition boiling of nitrogen in a large volume [2]: a) underheat $\Delta T_{sub} = 9$; b) ΔT_{sub} = 10 K; 2) P = 25 kPa; 2) 50; 3) 100; 4) 200; 5) 600; 6) 1200; 7) 2100.

The splitting of the boiling curves with respect to the underheat also illustrates well the role of unsteady heat conduction at the places of contact of the liquid with the wall in the transition boiling region.

Figure 8 [2] shows how the boiling curves of nitrogen vary in a large volume on a horizontal disk with a low-conductance coating, as the coating thickness increases. With increase of the coating thickness to $b_p < 100$ μm the boiling curve is displaced to the right, and is drawn out with respect to ΔT_w. It is evident from Eq. (7) and what was said above that, in this case, the increase of ΔT_{cr2} is determined by the increase of ε_{eff} (see Fig. 3) of the two-layer wall, which must be computed in Eq. (7) instead of ε_w.

The decrease of the slope of the boiling curve in the bubble boiling region is a consequence of the influence of unsteady effects on the growth of the bubbles. Upon separation of bubbles at the place of contact of liquid with the wall a lower and lower temperature is set up at the boundary of the contact as b_p increases, the time for heating (or cooling) of the liquid increases, the rate of growth of the bubbles decreases, and the coming into action of new vapor-forming centers is slowed down.

However, the start of transition boiling (point 1') for all $b_p < 100$ μm lies roughly on a single horizontal line, i.e., it is determined by the value

$$q_{1'} \cong (200-210)\ \mathrm{kW/m^2}.$$

This means that the start of transition boiling, i.e., the generation of regions occupied by vapor, and the degradation of heat removal set in roughly at the same intensity of bubble boiling, and are very likely due to subdividing of bubbles before they separate and generate vapor spots.

For a coating thickness of $b_p \geq 100$ μm the picture changes appreciably. The right-side boundary of the bubble boiling region is stabilized. This means that in Eq. (7) $\varepsilon_{eff} = \varepsilon_w$ = const, i.e., the thermal signal at the time of contact of the liquid and the wall does not pass through the coating, and the coating is perceived to be semiinfinite.

However, the left-side boundary of the transition boiling (the point 1', Fig. 1) is now located along the single vertical line $\Delta T_w \simeq 90$ K = const. This means that, independently of the intensity of bubble boiling and q_w, the occurrence of dry spots at this mean wall temperature already leads, for thermodynamic reasons, to a longer lifetime of the spots and the start of transition boiling. The almost parallel behavior of the bubble boiling curves for b_p = 120 and 160 μm can be explained by the increase of the heat-insulating role of the coating.

The influence of the rate of cooling $\partial T_w/\partial \tau$ is shown in Fig. 9 [1]. It can be seen that with increase of the cooling rate (or decrease of tube wall thickness) the heat-flux intensity in transition and film boiling and the slopes of the curves decrease. This is due to the complex combination of hydrodynamic stabilization of the vapor film (decrease of vapor generation), the changes in the nature of processes of unsteady heat conduction of the two-layer wall upon a noticeable temperature drop, even during the time of contact in transition boiling (especially for $b_w = 0.5$ mm), and the associated changes in the process of growth and subdivision of the vapor bubbles.

It is characteristic that the critical bubble boiling in this case is determined mainly by the wall temperature ΔT_{cr1}, which is independent of $\partial T_w/\partial\tau$.

In bubble boiling the decrease of the curve slope with increase of $\partial T_w/\partial\tau$ results from the fact that the vapor-generating centers active at large ΔT_w cannot stop the operation at small ΔT_w, and also that at large ΔT_w with increase of $\partial T_w/\partial\tau$ a progressively smaller number of mainly large centers are activated, which can operate even at small ΔT_w. In addition, with increase of $\partial T_w/\partial\tau$, after a cycle of growth of a vapor bubble, especially on a thin wall (see Fig. 4), T_w may decrease, slowing down the bubble growth rate and increasing the dwell time.

A pressure increase, as can be seen from Fig. 10 [2], displaces the boiling curve and, correspondingly, ΔT_{cr1} and ΔT_{cr2} to the left, to the region of smaller ΔT_w. This results from reducing the time of contact with the vapor [see Eqs. (4)-(6)].

We note that the validity of these formulas and of the explanation presented receive good confirmation from the influence of an increase of the underheat ΔT_s which, working in the opposite direction to the influence of pressure, increases the time of contact of the liquid with the wall, reduces the time of contact with the vapor, and shifts the boiling curve to the right (see Fig. 10).

Thus, with this unconventional analysis of critical boiling as a boundary of transition boiling and a special case of the smooth interchange of the bubble and film boiling regimes one can, first, elucidate in much more detail the mechanism of the influence of unsteady aspects on the boiling; second, verify that critical boiling, and also transition boiling as a whole, is determined by a complex combination of hydrodynamic and thermodynamic conditions; and, third, more meaningfully plan new investigations.

NOTATION

T, temperature; f, heat-transfer area; q, specific heat flux density; t, time; $\Delta T = T_w - T_s$, temperature head; $\Delta T_{sub} = T_s - T_L$, underheat of the liquid; σ, surface tension coefficient; θ, wetting angle; ρ, density; r, latent heat of vaporization; a, thermal diffusivity; b, thickness; R, radius; γ, orientation angle of the heater surface in space; h, height of roughnesses. Subscripts: b, phase boundary; cr1, critical bubble boiling (q_{max}); cr2, critical film boiling (q_{min}); 1', boundary between bubble and transition boiling; 2', boundary between film and transition boiling; lim, limiting value; L, liquid; v, vapor; s, saturation; sub, underheat; ct, coating; m, dry spot; T, heat conduction.

LITERATURE CITED

1. V. K. Koshkin, E. K. Kalinin, G. A. Dreitser, and S. A. Yarkho, Unsteady Heat Transfer [in Russian], Moscow (1973).
2. E. K. Kalinin, I. I. Berlin, and V. V. Kostiouk, Advances in Heat Transfer, Vol. 18 (1987), pp. 241-323.
3. T. Fujio, A. Mamora, and K. Kiroshi, J. Nucl. Sci. and Technol., 4, No. 3, 121-130 (1967).
4. P. J. Berenson, Int. J. Heat Mass Transfer, 5, 985-999 (1962).