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INFLUENCE OF THE THICKNESS OF A WALL AND OF ITS THERMOPHYSICAL CHARACTERISTICS ON THE CRITICAL HEAT FLUX IN BOILING

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The experimental data published by various authors who studied the burnout heat transfer in boiling have been analyzed. It is shown that the critical heat flux depends substantially on the physical properties of both the boiling liquid and cooled wall and its geometric parameters.

Keywords: *boiling, critical heat flux, wall thickness, thermal diffusivity.*

Introduction. The accident-free operation of technological equipment involving a boiling liquid as a heat-transfer agent presupposes the elimination of the burnout heat transfer. The diversity of heat transfer agents, dimensions, shapes, and of the material of heat-releasing walls, fluid velocities and pressures in the loop greatly complicates the choice of the parameters that provide for accident-free operation of equipment [1–6]. The study of the simplest case of the burnout heat transfer in pool boiling is needed to understand the mechanism underlying the onset of the thermal crisis and to carry out its mathematical description.

In [7], photographs are presented that fix the presence of dry and wetted spots on the heat-releasing wall in the precritical boiling regime. In these experiments, the vessel glass bottom covered by a thin layer of metal served as a heat-releasing wall. It is noted that each spot of the heat-releasing wall may turn to be dry for an instant of time, being covered again the next moment by a thin liquid film. As is shown in [8, 9], the local wall temperature in the precritical regime is in constant fluctuation about a certain average value of the wall temperature. The crisis is the phenomenon associated with a sudden extension of the dry spot on the wall being cooled and with the rise of the local wall temperature at the place where the dry spot extends. However, it should be kept in mind that the liquid that wets the wall in the form of a thin film penetrates there between growing agglomerates of vapor bubbles that serve as natural batchers of the liquid that cools the wall. If the amount of liquid is sufficient, the appearing dry spots are instantly covered by a thin film, and the crisis does not set in, but if the amount of the liquid that penetrates to the wall turns out to be smaller than a certain limit, the instantaneous extension of the dry spot becomes unavoidable. The boiling crisis should be considered as the choking regime in the section above the cooled wall, where a maximum void fraction is observed. The sudden extension of the dry spot on the cooled wall and the local growth of temperature are the consequences of the cooling liquid deficit as a result of the onset of the choking regime. The latter regime and drying-out of the thin film on the cooled wall must not be considered separately. The condition is observed here, when the drying-out of the film and the surge in the wall temperature result from the deficit of the liquid (in the regime of choking) from which the thin film on the body surface is formed.

In describing the burnout heat transfer, S. S. Kutateladze used the vapor velocity, which is easily calculated as the ratio $U_{\rm v,cr} = q_{\rm cr}/(r\rho_{\rm v})$, and assumed that the stability criterion k is const [10, 11]. Further calculations have shown that such an approximation can be considered as the first one in that limiting situation, but which generally is incorrect.

The analysis of experimental data given in what follows has shown that the stability criterion is a complex function that depends on the physical properties of the liquid and cooled wall, as well as on the geometric parameters of the latter. In the available models describing the boiling burnout heat transfer [10–14], neither the properties of the cooled wall nor its geometric parameters were taken into account.

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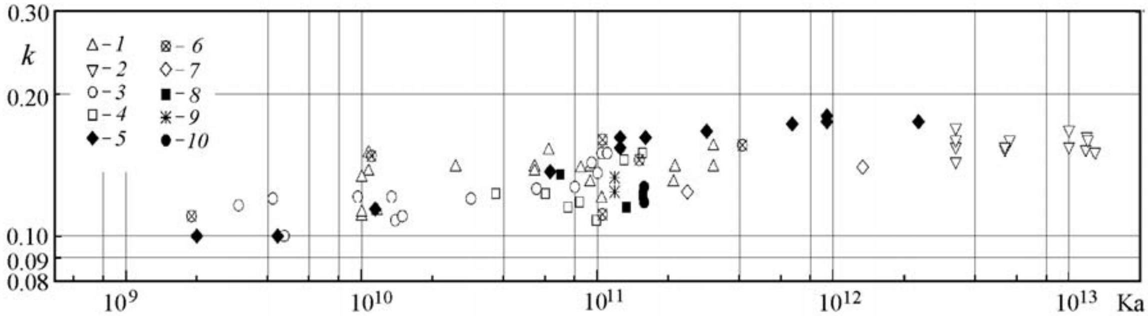

Fig. 1. Stability criterion vs. the Kapitsa number: 1) alcohols (methyl, ethyl, butyl) [18, 22, 27, 30, 37]; 2) water [18, 22, 29, 30; 3) Freons R21, R112, R113 [24, 31]; 4) benzene [20, 30]; 5) helium [36]; 6) nitrogen [34, 35]; 7) hydrogen [33]; 8) diphenyl [20]; 9) toluene [23]; 10) acetone [23].

Analysis of Experimental Data. Table 1 presents the data of various authors, as well as the dependence of the stability criterion on the dimensionless thickness of the wall and its physical properties. The table contains only those works that describe experimental procedures in detail, indicates the grade of the material from which a heat-releasing wall is made, and lists all the geometric characteristics of the cooled wall. To simplify the analysis, only experiments with a horizontally located heater were considered.

It should be emphasized once again that the dry-out of the thin film that leads to the burnout heat transfer in boiling is a consequence of the deficit of the liquid that arrives through the narrowest sections between the growing agglomerates of bubbles. Such a viewpoint allows one to analyze the works of various authors and calculate the values of the stability criterion at which the boiling crisis sets in as a function of other parameters in the experiments carried out by various researchers.

Influence of the physical properties of the liquid on the critical heat flux. Figure 1 presents experimental data processed in the coordinates

$$k = f(\mathrm{Ka}) . \tag{1}$$

The Kapitsa number Ka is the ratio of the two inner linear scales in liquid boiling:

$$\mathrm{Ka} = (l_\sigma / l_\mathrm{v})^6 = \sigma^3 / \left[\nu^4 \rho_\mathrm{liq}^2 (\rho_\mathrm{liq} - \rho_\mathrm{v})\, g\right] .$$

Here $l_\sigma = \sqrt{\dfrac{\sigma}{g(\rho_\mathrm{liq} - \rho_\mathrm{v})}}$ is the capillary constant of the liquid (the diameter of detaching bubbles is proportional to this parameter); $l_\mathrm{v} = \left[\dfrac{\nu^2}{g(1 - \rho_\mathrm{v}/\rho_\mathrm{liq})}\right]$ is the viscous-gravitational constant; this quantity determines the microlayer thickness under a growing vapor bubble [38, 39].

The experimental data of [18, 20, 22–24, 28–31, 34–37] were processed in the coordinates given in Eq. (1). The experiments were carried out with boiling of 14 different liquids. To eliminate or minimize the influence of the cooled wall properties on the magnitude of the critical heat flux, Fig. 1 contains the experimental results obtained in boiling on a thick-walled cooled wall made only from stainless steel or nichrome. To exclude the influence of capillary forces, the characteristic linear dimension of the heat-releasing wall that corresponded to the condition $\overline{D} \geq 2.0$ was used. It follows from the data presented that the stability criterion depends weakly on the Kapitsa number. The approximation dependence has the form

$$k = C_1\, \mathrm{Ka}^{0.05} . \tag{2}$$

The Kapitsa number in experimental investigations changed by four orders of magnitude. It follows from Fig. 1 that with decrease in the Kapitsa number the stability criterion decreases monotonically from 0.18 to 0.1.

TABLE 1. Critical Heat Fluxes in Boiling under Free-Convection Conditions

Substance	Pressure range P/P_{cr}	Heat-releasing wall			$Ka\cdot 10^{-10}$	k	$\frac{k}{Ka^{0.05}}\cdot 10^2$	$\left(\frac{\lambda C_p \rho_{liq}}{\lambda_w C_w \rho_w}\right)^{0.5}\cdot 10^2$	$\frac{\delta_w}{h_{cr}}$	Reference
		material	form	characteristic dimension, mm						
1	2	3	4	5	6	7	8	9	10	11
Water	Primary data are absent									[15]
Hydrogen	0.064–0.66	Karma alloy	Tape	b = 25.4, δ_w = 0.127	8–2.1	0.0725–0.104	2.1–2.6	14.2–46	0.053–0.091	[16]
n-pentane	0.03	Copper	Slab	—	13.7	0.135–0.15	3.6–4.1	1.1	∞	[17]
Water	$4.4\cdot 10^{-3}$–0.31	Nichrome	Tape	b = 6, δ_w = 0.5	330–1200	0.15–0.17	3.6–4.1	20–22	1.1–1.34	[18]
Ethanol	$1.5\cdot 10^{-2}$–0.48	Nichrome	Tape	b = 6, δ_w = 0.5	0.9–9.3	0.13–0.15	3.7–4.5	8–8.6	1.25–1.41	
Butanol	$2\cdot 10^{-2}$–0.61	Nichrome	Tape	b = 6, δ_w = 0.5	0.6–0.54	0.13–0.16	3.9–4.6	4.3–8	1.4–1.5	
Water	$4.4\cdot 10^{-3}$–0.87	Silver	Tube	D = 5, δ_w = 0.5	0.6–1400	0.08–0.12	2.2–2.8	5.1–6.8	0.15–0.25	[19]
Benzene	0.02–0.69	Stainless steel	Tube	D = 9.5, δ_w = 0.5	1.44–16.6	0.1–0.125	3.3–3.8	4.8–6.1	1.25–1.56	[20]
Diphenyl	0.09–0.75	Stainless steel	Tube	D = 9.5, δ_w = 0.5	7–18	0.11–0.14	3.1–3.9	5.5–6.5	1.3–1.4	
Nitrogen	0.013–0.75	Platinum sputtered on a disk	Disk	D = 66.5, δ_w = 0.051	0.0012–16.7	0.15–0.09	4.0–3.9	90–60	∞	[21]
Oxygen	0.016–0.9		Disk	D = 66.5, δ_w = 0.051	0.047–26.7	0.15–0.14	4.1–4.0	92–58	∞	
Water	$4.4\cdot 10^{-3}$–0.05	Stainless steel	Tube	D = 6.0, δ_w = 0.5	330–1200	0.15–0.17	4.5	21.7	1.1–1.34	[22]
Ethyl alcohol	$1.5\cdot 10^{-2}$–0.17	Stainless steel	Tube	D = 6.0, δ_w = 0.5	1–9.3	0.14–0.16	4.2	8.2–8.6	1.25–1.41	
Acetone	0.02	Stainless steel	Rod	D = 6.4	15.7	0.125	3.45	6.5	8.2	[23]
Toluene	0.025	Stainless steel	Rod	D = 6.4	11.8	0.133	3.7	5.5	8.3	
Propanol	0.02	Stainless steel	Rod	D = 6.4	1	0.112	3.5	5.5	8.2	
Butanol	0.02	Stainless steel	Rod	D = 6.4	1.2	0.113	3.6	7.2	8.3	
Freon R113	0.03–0.72	Stainless steel	Tube	D = 9.25, δ_w = 0.51	0.2–1.5	0.1–0.12	3.1–3.9	3.3–4.0	1.4–1.7	[24]
Freon R112	0.028	Stainless steel	Tube	D = 9.25, δ_w = 0.51	0.5	0.1	3.3	4.0	1.38	
Helium	0.43–0.95	Platinum	Disk	D = 9.91	0.2–230	0.1–0.19	3.4–5.1	108	—	[25]
Water	$4.4\cdot 10^{-3}$	Copper+silver	Disk	D = 50	330	0.18	4.3	5.7	∞	[26]
Water	$4.4\cdot 10^{-3}$–0.16	Nichrome	Tape insulated from below	b = 3–10, δ_w = = 0.5–1.0	330–1290	0.17–0.15	3.4–4.1	20–22	1.1–1.3	[27]
Methanol	0.02–0.69	Nichrome		b = 3–10, δ_w = = 0.5–1.0	6.2–31	0.14–15	3.7–4.0	8.6–8.8	1.25–1.35	
n-Propanol	0.02–0.85	Nichrome		b = 3–10, δ_w = = 0.5–1.0	1.0–2.1	0.12–0.14	3.3–4.2	7.6–8.2	1.25–1.4	
Water	$4.4\cdot 10^{-3}$	Stainless steel	Tube	D = 1.5, δ_w = 0.15	330	0.168	2.8	21.7	0.33	[28]
Water	$4.4\cdot 10^{-3}$	Stainless steel	Tube	D = 1.5, δ_w = 0.35	330	0.2	3.4	21.7	0.77	
Water	$4.4\cdot 10^{-3}$	Stainless steel	Tape	b = 8, δ_w = = 0.01–2.0	330	0.06–0.15	1.5–4.0	21.7	0.022–1.8	[29]
Water	$4.4\cdot 10^{-3}$–0.31	Nichrome	Tape	b = 6, δ_w = 0.5	330–1200	0.15–0.17	3.6–3.9	20–22	1.1–1.35	[30]
Ethanol	$1.5\cdot 10^{-2}$–0.8	Nichrome	Tape	b = 6, δ_w = 0.5	6.9–9.3	0.13–0.15	3.9–4.6	8–8.6	1.25–1.65	
Benzene	$2\cdot 10^{-2}$–0.22	Nichrome	Tape	b = 6, δ_w = 0.5	13.0–15.5	0.14–0.16	3.9–4.2	5.4–5.8	1.2–1.35	
Freon R21	0.042–0.75	Stainless steel	Tube	D = 3, δ_w = 0.5	0.42–11	0.12–0.15	3.7–4.1	3.6–5.0	1.34–1.6	[31]
n-Heptane	0.18–0.41	Gold sputtered on glass	Film	$\delta_w = 1\cdot 10^{-4}$	4–10	0.11–0.13	3.1–3.7	~27	136	[7]
Acetone	0.02	Copper	Disk	D = 63.5	15.8	0.15–0.16	4.2–4.4	1.33	∞	[32]
Isopropyl alcohol	0.015	Copper	Disk	D = 63.5	0.84	0.13	4.2	1.53	∞	
Methanol	0.0125	Copper	Disk	D = 63.5	4.5	0.14	4.2	1.73	∞	
Hydrogen	$5.5\cdot 10^{-3}$–0.7	German silver	Tube	D = 7, δ_w = 0.35	24–210	0.08–0.15	3–3.6	0.85–1.5	0.58÷1.3	[33]

TABLE 1. Continued

1	2	3	4	5	6	7	8	9	10	11
Nitrogen	0.03–0.9	Copper	Rod face	D = 10	0.19–15	0.14–0.16	4.1–4.6	1.6–1.08	∞	
Nitrogen	0.03–0.9	Brass	Rod face	D = 10	0.19–15	0.12–0.16	4.0–4.6	4.6–2.7	∞	[34]
Nitrogen	0.03–0.9	Stainless steel	Rod face	D = 10	0.19–15	0.11–0.16	3.8–4.6	13.4–8	∞	
Nitrogen	0.03	Copper	Rod face	D = 12	9.7	0.129	3.6	1.7	∞	
Nitrogen	0.03	Nickel	Rod face	D = 12	9.7	0.119	3.35	9.3	∞	[35]
Nitrogen	0.03	Stainless steel	Rod face	D = 12	9.7	0.111	3.1	13.7	∞	
Helium	0.1–0.85	Stainless steel	Disk	D = 25, δ_w = 3	0.2–94	0.091–0.178	3.1–4.6	~2.0	2.0	[36]
Ethanol	0.015–0.8	Stainless steel	Tape insulated from below	b = 5–50 δ_w = 0.5	0.9–9.3	0.135–0.155	4.0–4.2	8–8.6	1.25–1.65	[37]

Influence of the heat-releasing wall on the critical heat flux in boiling. An analysis of experimental data carried out in [15] has made it possible for the first time to establish the influence of the wall thickness on the magnitude of the critical heat flux in boiling under free-convection conditions. Moreover, it was shown there that q_{cr} at the same thickness depends on the heat-releasing wall material. Later studies [16–37] have confirmed both facts revealed in [15].

Below an analysis of the results of experiments with several liquids boiling on plates or tubes with different wall thicknesses and thermophysical properties is presented. The comparison was made under the condition where the critical heat flux was independent of the characteristic linear dimension of the wall ($\overline{D} \geq 2.0$) [30].

The physical explanation of the influence exerted by the thickness of the wall and its thermophysical properties on the critical heat flux magnitude is given in [5, 40]. It was stipulated there that the true value of the local heat flux under a growing vapor bubble may exceed by an order of magnitude the average value of the specific heat flux. On a thick-walled heater this heat flux is spent both to evaporate the liquid microlayer and to scatter heat by conduction. In a thin-walled heater the influence of heat conduction disappears or decreases many times. Precisely this leads to the general decrease in the critical heat flux with decrease in the wall thickness. The solution of the problem on heat transfer between a heat-releasing wall and the liquid boiling on it is replaced in [5, 40] by the solution of the problem on liquid film evaporation from the surface of a semi-infinite solid body with a constant initial temperature. The solution of the latter problem allows one to calculate the cooling depth from the expression

$$h_{cr} = 1.245\sqrt{a_w \tau_{gr}}\,, \tag{3}$$

$$\tau_{gr} = 2.1\sqrt[4]{\frac{\sigma}{g^3(\rho_{liq} - \rho_v)}}\sqrt{\frac{\rho_{liq}}{\rho_{liq} - \rho_v}}\,. \tag{4}$$

Subject to (4), expression (3) becomes

$$h_{cr} = 1.8\sqrt{a_w}\left(\frac{\sigma}{g^3(\rho_{liq} - \rho_v)}\right)^{1/8}\left(\frac{\rho_{liq}}{\rho_{liq} - \rho_v}\right)^{1/4}. \tag{5}$$

The last term in Eq. (5) should be taken into account in processing experimental data at $P/P_{cr} \geq 0.5$.

Figure 2 presents the data of experiments carried out in [16–37] with boiling on walls of different thicknesses and with different thermophysical properties; the data were processed in the coordinates

$$k/\mathrm{Ka}^{0.05} = f(\delta_w/h_{cr})\,. \tag{6}$$

The function of the right-hand side of Eq. (6) changed by three orders of magnitude, with the value of the dimensionless parameter $k/\mathrm{Ka}^{0.05}$ varying within 0.010–0.045. As is shown in Fig. 2,

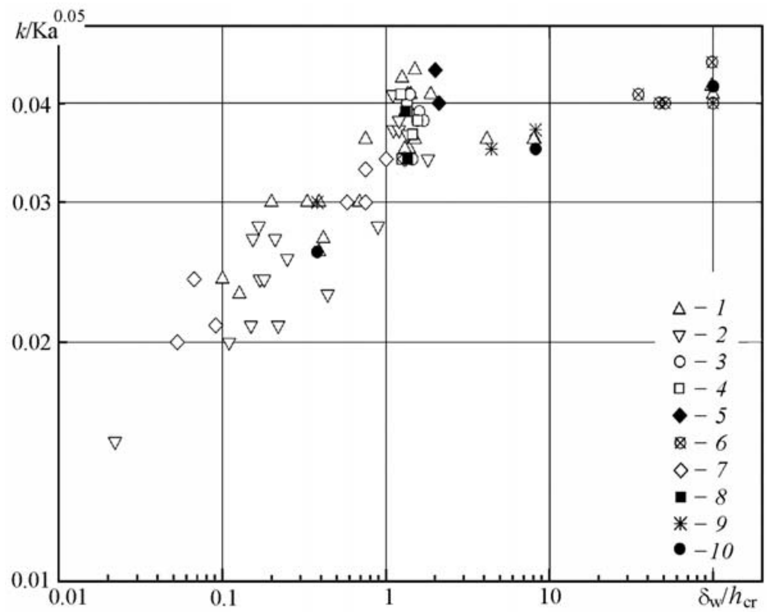

Fig. 2. Dimensionless complex $k/\mathrm{Ka}^{0.05}$ vs. the relative thickness of the heat-releasing wall: 1) alcohols [18, 22, 27, 29, 30, 37]; 2) water [18, 22, 26, 28–30]; 3) freons [24, 31]; 4) benzene [20, 30]; 5) helium [25, 36]; 6) nitrogen [34, 35]; 7) hydrogen [16, 33]; 8) diphenyl [20]; 9) toluene [23]; 10) acetone [23, 32].

$$k/\mathrm{Ka}^{0.05} = C_2\left(\frac{\delta_w}{h_{cr}}\right)^{0.2}. \tag{7}$$

At $\delta_w/h_{cr} \geq 1.0$ the parameter $k/\mathrm{Ka}^{0.05}$ may be considered independent of the relative wall thickness.

Mention should also be made of the good coincidence of the data on water boiling on a thin-walled silver pipe [19], obtained when the pressure varied in wide ranges, with the results of experiments in [29], where the thickness of a stainless steel tape was a variable parameter. The tests with boiling hydrogen published in [16, 33] where carried out at a pressure that varied in a wide range. The material of the wall and its thickness differed greatly in these works. However, when the results of measurements were processed in the coordinates (7), they coincided satisfactorily with the foregoing experimental data on water boiling. The data of other researchers presented in Fig. 2 only add to the dependence obtained.

Of special note are the results of measurements made on metal coatings sputtered onto glass walls. In [7, 8, 21] the thickness of the metal was measured in nanometers or microns. According to the experiments carried out in [5], thin coating from another metal does not exert any influence on the boiling crisis. It was established that the absolute values of the critical heat flux are determined by the thermophysical properties of the substrate.

If in the course of calculation of the cooling depth by Eq. (5) the thermal diffusivity of glass is adopted, then the data of experiments of [7, 8, 21] agree satisfactorily with the generalizing dependence given in Fig. 2. The results of the experiments require their physical explanation, which is absent at the present time. It can only be noted that glass has a low thermal conductivity and a very high heat capacity.

Independence of the critical heat flux on the complex criterion $\left(\frac{\lambda C_p \rho_{liq}}{\lambda_w C_w \rho_w}\right)^{0.5}$. The heat transfer in boiling depends greatly on the change in the complex criterion $\left(\frac{\lambda C_p \rho_{liq}}{\lambda_w C_w \rho_w}\right)^{n}$ [5, 41]. As is shown in [41], $n = -0.2$.

Figure 3 presents processed experimental data on burnout heat transfer in boiling in the coordinates

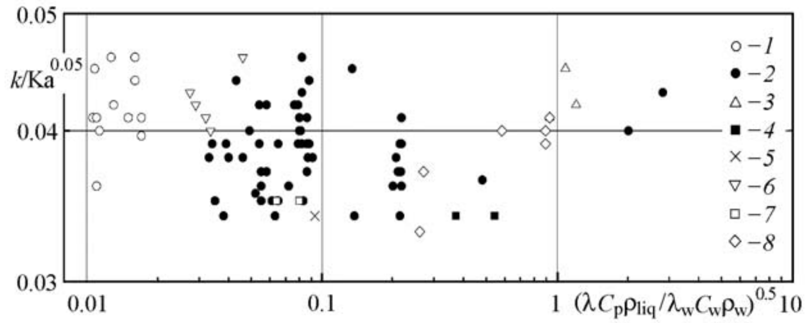

Fig. 3. Dimensionless complex $k/\mathrm{Ka}^{0.05}$ vs. the criterion $(\lambda C_p\rho_{liq}/\lambda_w C_w\rho_w)^{0.5}$: 1) copper (isopropyl, methyl, and propyl alcohols, water, acetone, nitrogen [17, 26, 32, 34, 35]); 2) stainless steel (ethyl, butyl, propyl, and methyl alcohols, water toluene, acetone, helium, benzene, diphenyl, nitrogen, freons [18, 20, 22–24, 27, 28, 30, 31, 34–37]); 3) platinum (helium [25]); 4) German silver (hydrogen [33]); 5) nickel (nitrogen [35]); 6) brass (nitrogen [34]); 7) inconel, monel (propanol [23]); 8) metal–glass (oxygen, nitrogen [21]).

$$k/\mathrm{Ka}^{0.05} = f\left(\frac{\lambda C_{gr}\rho_{liq}}{\lambda_w C_w \rho_w}\right)^{0.5} . \tag{8}$$

The comparison was made at $\overline{D} \geq 2.0$ and $\delta_w/h_{cr} > 1.0$. When the criterion $(\lambda C_p\rho_{liq}/\lambda_w C_w\rho_w)^{0.5}$ changed by more than two orders of magnitude, the dimensionless parameter $k/\mathrm{Ka}^{0.05}$ remained unchanged. It should be indicated that Fig. 3 presents experimental data on boiling of cryogenic liquids on the ends of rods made from different metals [21, 34, 35] and the data on water boiling at T_s = 560 K [30].

Attention should be focused on the results of [34], where it is shown that the critical heat fluxes in boiling of nitrogen on an end of a rod made from copper, brass or stainless steel were practically identical. The experiments were carried out at $0.03 \leq P/P_{cr} \leq 0.9$.

The thermophysical properties of liquids were borrowed from handbooks [5, 42–45], the physical properties of metals from [46–48], and the properties of glass from [49].

CONCLUSIONS

1. The critical heat flux in boiling depends greatly on the thickness of the heat-releasing wall and on its physical properties. The mathematical description of a boiling crisis is possible only by solving the problem with conjugate boundary conditions at the solid body–cooling liquid interface.

2. The attainment of the critical rate of vapor formation (choking regime) and the immediate growth of a dry spot on the wall is a consequence of one phenomenon, which is usually referred to as the burnout heat transfer in boiling.

3. The stability criterion does not remain constant but depends on the physical properties of a boiling liquid even when a horizontal thick-walled slab of infinite size is cooled.

NOTATION

a_w, thermal diffusivity, m^2/sec; b, width of a plate, mm; C_1 and C_2, constants in Eqs. (2) and (7); C_p and C_w, heat capacity of a liquid and wall, J/(kg·deg); D, diameter of a cooled cylinder (disk), mm; $\overline{D} = D/\sqrt{\frac{\sigma}{g(\rho_{liq} - \rho_v)}}$, dimensionless diameter; g, free fall acceleration, m^2/sec; h_{cr}, cooling depth calculated by Eq. (5), m; $k = \frac{U_v\sqrt{\rho_v}}{\sqrt[4]{\sigma g(\rho_{liq} - \rho_v)}} = \frac{q_{cr}}{r\sqrt{\rho_v}\ \sqrt[4]{\sigma g(\rho_{liq} - \rho_v)}}$, stability criterion of a two-phase flow; Ka, Kapitsa number; P and P_{cr}, pressure and critical pressure, N/m^2; q_{cr}, critical heat flux, W/m^2; r, latent heat of vapor generation, J/kg; t_w and t_s, wall temperature and saturation temperature, ^{o}C; T_w, wall temperature, K; $U_{v,cr}$, critical velocity of vapor, m/sec; δ_w, cooled wall thickness, m; δ_w/h_{cr}, dimensionless thickness of a cooled wall; $\Delta t = t_w - t_s$, temperature head, ^{o}C; λ_w and λ, thermal conductivity of metal and liquid, W/(m·deg); ν, kinematic viscosity, m^2/sec; ρ_w, ρ_{liq}, and ρ_v, density of metal, liquid, and vapor, kg/m^3; σ, surface tension, N/m; τ_{gr}, time of growth of bubble agglomerate, sec; φ, void fraction, %. Subscripts: cr, critical; gr, growth; liq, liquid; s, saturation; v, vapor; w, wall.

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