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HEAT TRANSFER IN BOILING OF LIQUID IN A FILM MOVING UNDER GRAVITY

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Experimental data on heat transfer in boiling in a film of liquid moving under gravity have been processed in dimensionless coordinates. A comparison between the data on heat transfer during boiling in a film with the data on heat transfer in pool boiling is carried out, which makes it possible to more accurately estimate the influence of the film flow velocity and spray entrainment on heat transfer in film boiling.

Keywords: *film flow, boiling heat transfer.*

Introduction. Film apparatuses are finding wider and wider application in industry: natural gas liquefiers, absorption transformers of heat, heat exchangers in chemical, refrigeration, and food industries. One of the factors hindering a wider application of evaporators of such a type is the absence of well-verified dependences allowing one to carry out calculations of heat transfer in film boiling and evaluate the associated critical heat fluxes. The aim of this article was to compare data on heat transfer in film boiling with data on pool boiling heat transfer. Such a comparison allows one to more distinctly reveal the characteristic features of heat transfer in film boiling and evaluate the influence of film flow velocity and spray entrainment on film boiling heat removal, as well as other characteristic features of this process.

The comparison is based on the well-known regularity treated in [1], where the data on water boiling in a tube were compared with those on pool boiling. It was shown that at a high heat flux the ratio of heat transfer coefficients for tube boiling and pool boiling tended to unity. The higher the liquid circulation velocity in a tube, the higher is the heat flux density at which $\alpha/\alpha_0 \to 1.0$.

Analysis of Experimental Data. Experimental investigations [2–11] are devoted to the study of boiling heat transfer. Variable quantities in them were the physical properties of liquid in a film, wetting density, heat flux, material of a heat-releasing wall, and the geometric parameters of the latter. Works [2–5, 8] are devoted in the main to investigations of heat transfer in film evaporation. The initial stage of boiling studied by the authors of those works exerts no substantial influence on the heat transfer intensity. In [6, 7, 9–11], the heat flux varied in wide limits, up to its critical value. At high heat fluxes the contribution of boiling is so high that the average heat transfer coefficient practically does not depend on the wetting density. In investigations of boiling heat transfer, it is customary to distinguish two Reynolds numbers, one of which is based on the average film velocity $\left(\mathrm{Re} = \frac{\overline{U}\overline{\delta}}{\nu} = \frac{\Gamma}{\mu}\right)$ and the other on the vapor generation rate $\left(\mathrm{Re}_* = \frac{q l_\sigma}{r \rho_v \nu}\right)$.

It is shown in [2–5] that at small values of q (evaporation and the initial stage of boiling) heat transfer is governed in the main by the wetting density, i.e., by the Re number. In the case of developed boiling, heat transfer depends on the vapor generation rate, i.e., on the Re_* number. A basic characteristic feature observed by the authors of works [4, 6, 10, 12] with the aid of high-speed cine filming is the mechanism of growth of a vapor bubble usually occurring in two steps. A bubble nucleates in a depression on a heat-releasing wall. However, in its minimal size the bubble is separated from the wall and gets into a superheated layer of liquid. Its further growth is connected only with the liquid whose layer separates it from the wall. The schematic of the growth of the bubble [6] is shown in Fig. 1. It is seen that for this reason a change in the wall roughness in film boiling leads to a different law than in pool boiling. Thus, in [4] the roughness of a vertical copper tube with water film boiling changed from 2 to 12 μm. The

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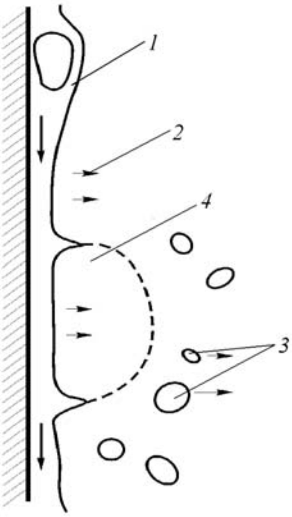

Fig. 1. Schematic of growth and collapse of a vapor bubble in liquid film boiling: 1) film of liquid; 2) vapor flow in boiling; 3) drops of liquid; 4) vapor bubble.

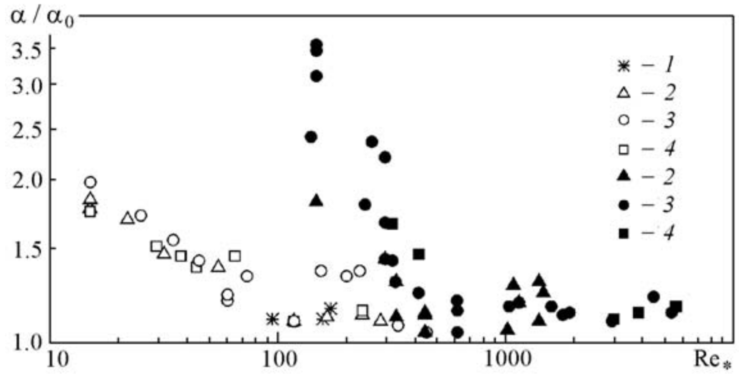

Fig. 2. Change of the relative heat transfer coefficient as a function of the Re_* number (light dots 1–4, Freons R11 [7]; R12 [5]; R113 [7]; FC-72 [9]; dark dots, water [6, 7]): 1) Re = 150, 2) 400–600; 3) 800–1500; 4) 2800–3700.

author noted that he did not reveal the influence of the wall roughness on boiling heat transfer when the roughness changed from 2 to 12 μm. However, the indentation of artificial pores of depth from 0.2 to 0.3 mm of the same diameter lead to heat transfer enhancement. In the inferences in [4] the author claimed that few random macropores 1–2 times exceeding in size the dimensions of roughness considerably improved the heat transfer. Another most important characteristic feature of film boiling of liquid is the entrainment of a portion of liquid from a film on vapor bubble collapse. Figure 1 shows the scheme (from [6]) of film flow in boiling of liquid that wets a vertical wall. The diameter of the separating vapor bubbles much exceeds the film thickness, and on departure of a bubble its collapse accompanied by liquid spraying into space occurs. For the first time, this phenomenon with quantitative determination of the mass of the liquid entrained from the film was investigated in [13]. In [6, 7], similar experiments were accompanied by simultaneous measurements of the boiling heat transfer rate. This made it possible to evaluate the influence of entrainment on the heat transfer intensity in boiling of liquids with different physical properties.

Table 1 cites relevant works with the indication of a working substance and the basic parameters of experimental investigation. Figure 2 compares data on heat transfer in film boiling with those on pool boiling.

It should be kept in mind that at small heat fluxes boiling can exist only on part of the test section, and the local heat transfer coefficient over the test section length changes significantly in this case [5]. In developed boiling the heat transfer coefficient practically does not change over the test section length [14]. In Fig. 2 and Table 1 experi-

TABLE 1. Heat Transfer in Film Boiling

Substance	Wall material	L, m	R_z, μm	D; b, mm	$q \cdot 10^{-3}$, W/m^2	Re	Re$_*$	$\frac{\alpha}{\alpha_0}$	$\overline{U}$	Reference
Water	Copper	1.2	–	30	23–160	550–1570	148–1036	1.52–1.0	–	[2]
R11	Brass	0.6	4.4	32	25	800	100	1.31	–	[3]
Water	Copper	2.0	2–12 Micrpores 0.2–0.3 mm	46	(2.6–36)	900–1800	150–300	3.4–2.2	–	[4]
R12	Steel St45	1.2	–	16	6–24	570–3400	15–60	2–1.23	–	[5]
Water	Stainless steel	0.6–1.0	–	16	140–300	500–1250	900–1900	1.2–1.05	0.25–0.7	[6]
Water	Same	0.18	–	8.0	160–1100	1100–3350	1100–7000	1.25–1.1	1.52–4.0	[7]
R113	»	0.18	–	8.0	22–80	1800–3800	63–230	1.3–1.4	1.67–9.84	[7]
R11	»	0.18	–	8.0	30–120	1700–3600	110–450	1.05–1.1	0.52–1.97	[7]
Water	»	0.591	–	27.5	22–60	1300	140–383	2.4–1.3	–	[8]
FC-72	Copper	0.127	–	b = 25.4	50–140	420–1960	118–330	1.25–1.12	–	[9]
Water	Brass	0 .93	–	60.3	56–69.4	550–1125	332–493	1.3–1.05	–	[10]
Nitrogen	Duralumin	$64 \cdot 10^{-3}$	3.0	b = 67	15–27	71–155	95–170	1.1–1.16	–	[11]

mental data of [2–11] are presented at film Reynolds numbers of about 150, 500, 1000, and 3500 in boiling of water, Freons R12, R113, R11, FC-72, and of nitrogen. The boiling heat transfer coefficients under the conditions of high heat-transfer rate are determined from the dependence

$$\mathrm{Nu}_0^* = 0.01\mathrm{Re}_*^{0.8}\mathrm{Pr}^{1/3}\overline{b}K^{0.4}\left(\frac{\lambda C_p \rho_{\mathrm{liq}}}{\lambda_{\mathrm{w}} C_{\mathrm{w}} \rho_{\mathrm{w}}}\right)^{-0.2}, \tag{1}$$

which is valid in boiling of liquid on a thick-walled heat-releasing wall when heat transfer is independent of wall roughness. Dependence (1) includes a complex with the thermophysical properties of a cooled wall and, as shown in [15], satisfactorily correlated a great number of experimental data on pool boiling of liquids.

In [16, 17], it is emphasized that with decrease in the film thickness the ratio of the quantity of heat removed by vapor bubbles and evaporation undergoes a change — the smaller the film thickness, the more significant is the role of evaporation. It is emphasized in [16, 17] that on decrease in the film thickness, the number of vapor bubbles decreases considerably. In [17], it is noted that at q = idem the wall temperature drops on decrease in the film thickness, and deactivation of the acting nucleation sites occurs. On a thin film vapor bubbles travelling over the heat-releasing wall appear. New bubbles arise at the site of destruction of previous ones. The bubble nucleus is not connected with the microdepression on the wall.

As is seen from Table 1, the authors of [2, 5–10] do not present quantitative characteristics of the finish classes of test sections. If we assume that those were technical-grade surfaces, then, according to [4, 6, 10, 16–18], the influence of roughness may be neglected.

The processed data presented in Fig. 2 do not take account of the influence of wall roughness on heat transfer in film boiling. The assumption that in [2–10] experiments were carried out on technical-grade surfaces introduces some uncertainty into the results of processing of these data. A circumstantial evidence of the validity of this hypothesis is a satisfactorily coincidence of all the experiments shown in Fig. 2 among themselves in the region of developed boiling.

The data presented in Fig. 2 allow us to consider that in the case of boiling of Freons and $\mathrm{Re}_* > 150$ the heat transfer rate is independent of the wetting density but is governed only by boiling, since $\alpha/\alpha_0 \to 1.0$. When $\mathrm{Re}_* < 150$, combined heat transfer occurs when the contribution by boiling to the integral value of the heat transfer coefficient decreases with the Re$_*$ number, i.e., with the heat flux. In the case of water boiling at $\mathrm{Re}_* > 800$ (dark dots in Fig. 2), the heat transfer rate is independent of the wetting density. In the case of mixed heat transfer a consider-

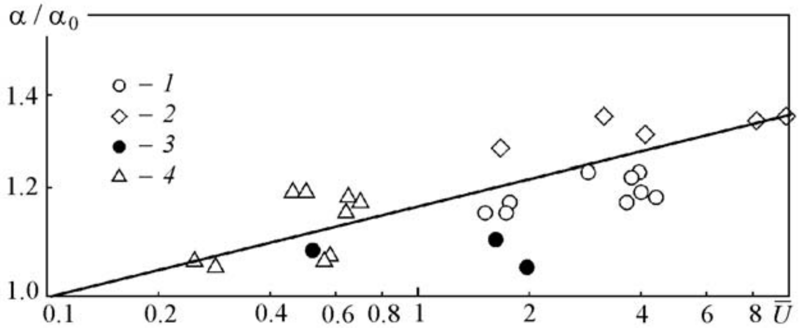

Fig. 3. Influence of spray entrainment on boiling heat transfer: 1) water [7]; 2) R113 [7]; 3) R11 [7]; 4) water [6].

able spread of experimental data is observed which may depend substantially on the experimental technique. The most probable is the manifestation of hysteresis with increase and decrease in the heat flux.

It should be emphasized that the relative heat transfer coefficient (Fig. 2) exceeds unity by 10–25% even at $\mathrm{Re}_* > 150$ for Freons and $\mathrm{Re}_* > 800$ for water. It may be assumed that growth and departure of a bubble and the accompanying spray entrainment lead to some heat transfer enhancement. In Fig. 3 the data on spray entrainment and heat transfer presented in [6, 7] have been processed in the coordinates

$$\alpha/\alpha_0 = f(\overline{U}) \,. \tag{2}$$

It is seen that with increase in spray entrainment the relative heat transfer coefficient increases. The data given can be approximated by the relation

$$\alpha/\alpha_0 = C\overline{U}^{\,0.1} \,. \tag{3}$$

Equation (3) can correlate the available experimental data, but cannot be used for calculation, since the amount of the liquid entrained is unknown.

As shown in [6], $\overline{U} = f\left(\mathrm{We}\left(\frac{\rho_{\mathrm{v}}}{\rho_{\mathrm{liq}}}\right)^{0.8}\right)$. If in the Weber number we take the capillary constant of the liquid as the linear dimension, then this number will acquire the form

$$\mathrm{We} = \left(\frac{q}{r\rho_{\mathrm{v}}}\right)^2 \frac{\rho_{\mathrm{v}}}{\sigma^{1/2} g^{1/2} (\rho_{\mathrm{liq}} - \rho_{\mathrm{v}})^{1/2}} = \frac{U_{\mathrm{v}}^2 \rho_{\mathrm{v}}}{g^{1/2} (\rho_{\mathrm{liq}} - \rho_{\mathrm{v}})^{1/2} \sigma^{1/2}} \,.$$

The experimental data (Fig. 4) obtained in [6, 7, 9–11], where investigations were carried out at heat fluxes up to the crisis and there was entrainment of liquid, can be presented as

$$\frac{\alpha}{\alpha_0} = f\left(\mathrm{We}\left(\frac{\rho_{\mathrm{v}}}{\rho_{\mathrm{liq}}}\right)^{0.8}\right). \tag{4}$$

It is seen that an increase in the amount of the liquid entrained from the film on collapse of a vapor bubble leads to a weak enhancement of boiling heat transfer. Intensification of heat transfer of any value begins when $\mathrm{We}(\rho_{\mathrm{v}}/\rho_{\mathrm{liq}})^{0.8} > 10^{-6}$.

The dependence that governs heat transfer in developed film boiling can be presented in the form

$$\mathrm{Nu}^* = 0.01\mathrm{Re}_*^{0.8}\mathrm{Pr}^{1/3}\overline{b}K^{0.4}\left(\frac{\lambda C_p \rho_{\mathrm{liq}}}{\lambda_{\mathrm{w}} C_{\mathrm{w}} \rho_{\mathrm{w}}}\right)^{-0.2} k \,, \tag{5}$$

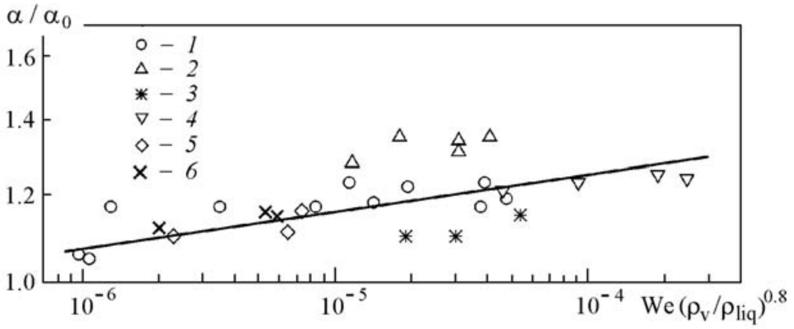

Fig. 4. Dependence of the relative heat transfer coefficient on the complex criterion $\mathrm{We}\left(\frac{\rho_\mathrm{v}}{\rho_\mathrm{liq}}\right)^{0.8}$: 1) water [7]; 20 R113 [7]; 3) R11 [7]; 4) water [6]; 5) FC-72 [9]; 6) nitrogen [11].

where $k = f\left(\mathrm{We}\left(\frac{\rho_\mathrm{v}}{\rho_\mathrm{liq}}\right)^{0.8}\right)$ according to the data given in Fig. 4. In the work analyzed the coefficient k varied within $1.0 \le k \le 1.25$.

Conclusions. In developed bubble boiling the intensity of heat transfer is independent of the wetting density, and in the first approximation can be calculated from an equation that describes boiling heat transfer under the conditions of free convection, when it does not depend on the heat-releasing wall roughness. Liquid entrainment from a film on vapor bubble collapse intensifies boiling heat transfer only insignificantly. The physical reason for such an action of a collapsing bubble on a film has not been determined unambiguously.

NOTATION

a, thermal diffusivity, m^2/s; b, channel width, mm; $\bar{b} = [1 + 10(\rho_\mathrm{v}/(\rho_\mathrm{liq} - \rho_\mathrm{v}))^{2/3}]$, nondimensional parameter; C_p, C_w, heat capacities of a liquid and wall, J/(kg·deg); D, diameter of a tube, mm; $\overline{D} = D/\sqrt{\frac{\sigma}{g(\rho_\mathrm{liq} - \rho_\mathrm{v})}}$, dimensionless diameter; g, free fall acceleration, m^2/s; $K = \frac{(r\rho_\mathrm{v})^2 l_\sigma}{C_p T_\mathrm{s} \rho_\mathrm{liq} \sigma}$, thermal similarity criterion; L, test section length, m; $l_\mathrm{v} = (\nu^2/g)^{1/3}$, viscous gravitation constant, m; $l_\sigma = \sqrt{\frac{\sigma}{g(\rho_\mathrm{liq} - \rho_\mathrm{v})}}$, capillary constant, m; m, spray entrainment rate, kg/s; $\mathrm{Nu}_0^* = \alpha_0 l_\sigma/\lambda$, $\mathrm{Nu}^* = \alpha l_\sigma/\lambda$, Nusselt numbers in pool boiling and film boiling; $\mathrm{Pr} = \nu/a$, Prandtl number; q = specific heat flux, W/m^2; R_z, height of asperities on a heat-releasing wall, μm; $\mathrm{Re} = \frac{\overline{W}\overline{\delta}}{\nu} = \frac{\Gamma}{\mu}$, film Reynolds number; $\mathrm{Re}_* = q l_\sigma / r \rho_\mathrm{v} \nu$, Reynolds number based on vapor generation rate; r, latent heat of vapor generation, J/kg; t_w, t_s, wall temperature and saturation temperature, $^\mathrm{o}$C; T_s, saturation temperature, K; $\overline{U} = mr/q$, ratio of spray entrainment rate to vapor generation rate; W, velocity of liquid in a film, m/s; $\mathrm{We} = U_\mathrm{v}^2 \rho_\mathrm{v} l_\sigma/\sigma$, Weber number; α, α_0, heat transfer coefficient in film boiling and pool boiling, W/(m^2 grad); δ_w, δ, wall thickness and film thickness, m; Γ, wetting density, kg/(m·s); λ_w, λ, thermal conductivity of a wall and film, W/(m·deg); $\sqrt{\lambda C_p \rho_\mathrm{liq}/\lambda_\mathrm{w} C_\mathrm{w} \rho_\mathrm{w}}$, ratio of physical properties of liquid to those of a cooled well; μ, ν, dynamic and kinematic viscosities of liquid, Pa·s, m/s; ρ_liq, ρ_v, densities of liquid and vapor, kg/m^3; σ, surface tension, N/m. Subscripts: liq, liquid; s, saturation; v, vapor; w, wall; 0, in a large volume; overbar, sign of averaging or of nondimensional parameter.

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