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HYDRODYNAMIC ASPECT OF THE EFFECT OF THE THERMOPHYSICAL PROPERTIES OF THE HEATER ON THE CRITICAL HEAT FLUX IN BULK POOL BOILING OF HELIUM

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The article examines the hydrodynamic aspect of the effect of the thermophysical properties of the heater on the critical heat flux in pool boiling of helium.

The recently begun promising utilization of superconductivity stimulated interest in processes of heat exchange in cryogenic liquids near critical bulk boiling. Several authors [1-4] draw attention to the distinct influence of the thermophysical properties of the heater on the first critical heat flux. Sometimes the assumption is expressed that it is impossible to take this phenomenon into account within the framework of the hydrodynamic theory (e.g., [4]). We want to point out that the attempt of Grigor'ev et al. [4] to take into account the effect of the properties of the heater material on the first critical heat flux leads to the known formula of the hydrodynamic theory, and all the corrections connected with the properties of the material vanish if the exact solution is used instead of the interpolation formula (7) from the article by Grigor'ev et al. [4].

Below we present a physical model of the effect of the thermophysical properties of the heater on the maximum critical heat flux in boiling of helium, corresponding to the hydrodynamic nature of the crisis.

The hydrodynamic hypothesis explains the first critical heat flux density by infringement of the structure of the two-phase layer near the heater, and its rearrangement [5]. Here we

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TABLE 1. Change of the Complex $\varkappa/(\varkappa+1)$

Liquid, T', K	Copper		Bronze		Nickel		Brass		Stainless steel	
	$\varkappa$	$\frac{\varkappa}{\varkappa+1}$	$\varkappa$	$\frac{\varkappa}{\varkappa+1}$	$\varkappa$	$\frac{\varkappa}{\varkappa+1}$	$\varkappa$	$\frac{\varkappa}{\varkappa+1}$	$\varkappa$	$\frac{\varkappa}{\varkappa+1}$
Helium, 4.2	5,35	0,84	1,42	0,59	1,42	0,59	0,96	0,49	0,33	0,23
Hydrogen, 20	17,04	0,94	2,68	0,73	3,42	0,77	—	—	1,55	0,61
Nitrogen, 77	41,4	0,98	14,1	0,93	17,9	0,94	22,3	0,94	6,09	0,86
Oxygen, 90	51,9	0,981	13,5	0,931	16,5	0,943	21,1	0,95	5,19	0,84

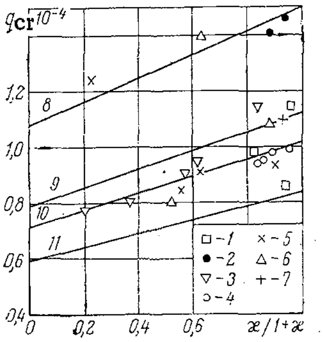

Fig. 1. Comparison of the experimental data on the first critical heat flux density in boiling helium on surfaces of different materials: 1) data of [1]; 2) [2]; 3) [4]; 4) [11]; 5) [12]; 6) [13]; 7) [14]; 8) dependence (9) for k = 0.22; 9) 0.16; 10) 0.145; 11) 0.12. q_{cr}, W/m².

assume for the sake of simplicity that all the heat supplied to the heater is removed by evaporation. Nevertheless, it is known [6, 7] that turbulization of the boundary layer by vapor bubbles makes an additional contribution to the removal of heat. Replacing detached bubbles, moles of cold liquid touch the heating surface and cool down on account of non-steady-state heat conduction. It was observed in experiments that the surface temperature drops after a bubble becomes detached. Thus, the heat is removed from the heater in two ways: by evaporation of the liquid and by non-steady-state heat conduction. We will not examine natural convection. In accordance with this hypothesis we write the expression for the critical heat flux in the form

$$q_{cr} = q_K + q_H \tag{1}$$

or

$$\frac{q_{cr}}{q_K} - 1 = \frac{q_H}{q_K}. \tag{2}$$

It is indispensable to determine the ratio q_H/q_K. To find its exact value, we do not have at present sufficiently full information on the process, we will therefore estimate the value according to the relative contribution of the latent heat of vaporization Q_K and non-steady-state heat conduction Q_H to the single act of bubble growth and detachment. For the sake of simplicity we neglect the heat required for superheating the liquid, and thus we find that the heat expended on the formation of a bubble with radius R_0 by evaporation is equal to

$$Q_K = r\rho'' \frac{4}{3}\pi R_0^3. \tag{3}$$

For estimating Q_H we will assume that at the time of bubble growth and detachment, moles of cold liquid with temperature T' penetrate impulsively to the heating surface whose temperature is T_{CT}. At the time of penetration of such pulsations, a heat flux q originates owing to the non-steady-state heat conduction [8]:

$$q = \frac{\Delta T}{\sqrt{\pi t}}\left(\frac{\sqrt{\lambda c\rho}}{1+\sqrt{\lambda c\rho/\lambda' c'\rho'}}\right), \qquad (4)$$

where $\Delta T = T_{CT} - T'$. Magnitudes with primes relate to characteristics of the liquid, without prime to the heater. We adopt as characteristic the scale of pulsations R_0, and as characteristic time t_0. If we integrate (4), we obtain

$$Q_{\text{н}} = \sqrt{\pi}\, R_0^2 2\sqrt{t_0}\,\Delta T\left(\frac{\sqrt{\lambda c\rho}}{1+\sqrt{\lambda c\rho/\lambda' c'\rho'}}\right). \qquad (5)$$

Since a vapor bubble in liquid helium grows chiefly in the layer of superheated liquid, we have from the Plesset—Zwick ratio that

$$\Delta T\sqrt{t_0} = \frac{1}{2}\sqrt{\frac{\pi}{3}}\,\frac{r\rho'' R_0}{\sqrt{\lambda' c'\rho'}}. \qquad (6)$$

From (5), (6), (3)

$$\frac{Q_{\text{н}}}{Q_{\text{к}}} = \frac{\sqrt{3}}{4}\,\frac{\varkappa}{1+\varkappa}, \qquad (7)$$

where $\varkappa = (\lambda c\rho/\lambda' c'\rho')^{1/2}$.

Since pulsating motion of the cold liquid is due to the growth and detachment of a single bubble, and the density of evaporation centers and the frequency of detachment in the critical regime are determined by the origin of the unstable structure of the near-wall two-phase layer, it may be assumed that

$$\frac{q_{\text{н}}}{q_{\text{к}}} = \frac{Q_{\text{н}}}{Q_{\text{к}}} = \frac{\sqrt{3}}{4}\,\frac{\varkappa}{1+\varkappa}. \qquad (8)$$

If we use the known expression for q_K [5] and substitute (8) into (2), we obtain

$$q_{\text{cr}} = k\left(1+\frac{\sqrt{3}}{4}\,\frac{\varkappa}{1+\varkappa}\right) r\sqrt{\rho''}\,\sqrt[4]{g\sigma(\rho'-\rho'')}, \qquad (9)$$

where the double primes indicate that the parameters relate to the vapor phase.

Thus, the effect of the thermophysical properties of the material of the heater on the hydrodynamics found expression in the form of the criterion of stability. It follows from (9) that its dependence on the type of liquid is characterized by different contributions of non-steady-state heat conduction to heat transfer in the boiling of different liquids. The slight change of the complex $\varkappa/(1+\varkappa)$ for liquids with fairly high simmering temperature explains the insignificant effect of the thermophysical properties of the material of the heater on q_{cr}. The change of this complex may be followed in Table 1 which was compiled from data of [3].

The effect of the thermophysical properties of the heater on q_{cr} was obtained from the hydrodynamic treatment of the crisis by taking into account the component of the heat flux determined by turbulization of the motion of the liquid by bubbles becoming detached from the heater. For homogeneous media an analogous effect of the properties of the material of the pipe on heat exchange manifests itself on account of the turbulent pulsations of the flow velocity in the region near the wall [9, 10]. The change of intensity of heat transfer to liquids from heaters made of different materials was examined in detail in [3].

A comparison of dependence (9) with the experimental data for helium is shown in Fig. 1. To express the natural scatter of the data correlated by Zuber's evaluations with the probabilistic nature of the crisis, dependence (9) is represented for the minimum, mean, and maximum values of k equal to 0.12, 0.145, and 0.16, respectively. To maintain correspondence with the theoretical model, the experimental values q_{cr} were taken only for thick flat specimens whose heat transferring surface in a large volume is turned upward.

It can be seen from the graphs that the experimental points separate. Eighty percent of the measurements coincide with dependence (9) for $k = 0.145$ with an error not exceeding 20%. The measurements of [11] lie particularly close to the theoretical dependence. It should be pointed out that in this series q_r and $\varkappa$ were measured, and the variation of $\varkappa$ was attained without changing the physicochemical and mechanical properties of the heating surface. We also note that in each series of measurements we always found that q_{cr} increased when $\varkappa$ increased. An exception was only experiments with stainless steel which, together with data of [2], were situated close to dependence (9) with $k = 0.22$. From the descriptions in these works it may be assumed that heat escaped through the thermal insulation of the heater, the escape inducing a very nonunivariate heat flux on the heating surface that leads to bubble and film boiling. The realization of mixed boiling is accompanied by the appearance of a temperature gradient on the heat transferring surface and an increase of its mean temperature. These phenomena were observed in experiments, and they characterize transient boiling which was not examined within the framework of the present article.

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NOTATION

$q_K = kr\sqrt{\rho''}\sqrt[4]{g\sigma(\rho' - \rho'')}$; q_H, part of the thermal flux connected with unsteady heat conduction; Q_K, amount of heat expended on bubble formation by evaporation; Q_H, amount of heat transferred on account of non-steady heat conduction; T_{CT}, temperature of the heater surface; T', temperature of the liquid; λ, thermal conductivity; c, specific heat; ρ, density; t, time; R_0, detachment radius of a bubble; t_0, time of bubble growth; r, latent heat of vaporization; g, acceleration of gravity; σ, surface tension; k, criterion of stability of the structure of the two-phase layer.

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