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CRITICAL HEAT-FLUX DENSITY IN OPEN CHANNELS COOLED BY HELIUM II

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A generalized dependence is given for determining the critical heat-flux density in uniformly heated open channels cooled by He II.

Earlier [1], the basic results obtained for uniformly heated open channels cooled by naturally circulating helium II were given:

1) the quantity q_{cr} depends significantly on the temperature in the bath, and has a maximum at $T \simeq 1.9°K$;

2) the value of q_{cr} increases with change in slope of the channel from $\varphi = 0$ to $\varphi = 90°$;

3) the value of q_{cr} decreases with increase in relative length of the channel, $q_{cr} \sim (l/d)^{-1.5}$;

4) the value of q_{cr} does not depend on the immersion depth of the open channel in the bath;

5) propagation of the heat-transfer crisis over the whole length of the channel occurs practically instantaneously.

In the discussion and analysis of the experimental data, it was necessary to take into account that there are in fact two current trends in investigating the heat transfer in He II.

The first is the investigation of heat transfer at the liquid–solid boundary, including the investigation of various conditions of so-called nonpellicular boiling (conditions of "Kapitsa resistance" being one such). The results of [1] may be written, when speaking of the simplest examples, in various forms of functional dependence on the ratio $\Delta T/T$

$$\alpha_0 = 4\sigma_B T^3 f\left(\frac{\Delta T}{T}\right), \tag{1}$$

$$\alpha_0 = \frac{16\pi^4 k_b \rho w_F}{15 h \rho_S w_t^3} F\left(\frac{w_t}{w_l}\right) T^3. \tag{2}$$

Here the power index on T is sometimes significantly different from those in Eqs. (1) and (2) [2, 5].

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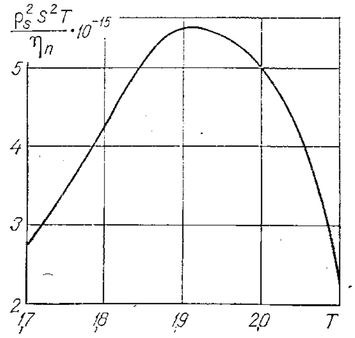

Fig. 1. Dependence of the complex $\frac{\rho_s^2 S^2 T}{\eta_n}\left(\frac{W}{m^3 \cdot {}^\circ K}\right)$ on the He-II temperature (°K).

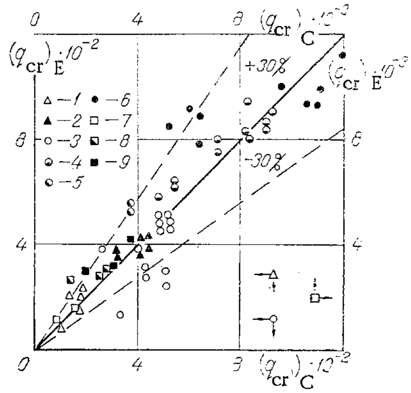

Fig. 2. Comparison of experimental values of q_{cr} (W/m²) with calculations using Eq. (13): 1, 2) d = 0.8 mm, l/d = 85, φ = 0, 90°; 3-6) d = 1.8 mm, l/d = 44, φ = 0, 45, 30, 90°; 7-9) d = 2.8 mm, l/d = 20.8, φ = 0, 45, 90°.

The second trend is the determination of the critical heat-flux density, i.e., the conditions at which the surface temperature of the heated wall sharply increases, a vapor phase appears between the solid wall and the liquid helium II. For the overwhelming majority of experimental conditions, the appearance of a layer of He I between the solid wall and the He II, which has been mentioned by several authors, is impossible: this follows from the diagram of state for helium. This aspect also includes investigations directed towards determining the so-called effective (apparent) thermal conductivity k_{ef}. The basic aim of such investigations is the attempt to trace the influence of the liquid temperature and its thermophysical properties, the immersion depth and certain geometric dimensions of the heated objects on the quantity q_{cr} or k_{ef}. As an example, typical dependences of the following form may be cited

$$k_{ef} = C(T)\, T\eta^{1/3}\rho^{2/3}S^{4/3}(\mathrm{grad}\, T)^{-2/3}. \tag{3}$$

Within the scope of the present work, it is only possible to consider the dubiousness of a few assumptions adopted in deriving such relations. The important thing to note is that the forms of generalization of investigations of the first and second of these trends have nothing whatsoever in common.

The above-noted trends are clearly evident in the literature data. Since most of the literature sources have been generalized in the reviews [2, 3], reference here will be made to them, with certain exceptions. Study of [2, 3] confirms a completely different approach to the investigation of the interrelated problems: the heat transfer at the boundary between the solid and the helium II and the evacuation of heat in the liquid from the interface (determination of k_{ef}).

In fact, in considering experiments to measure the thermal resistance of a He-II column ($\Delta T/Q$) or the effective thermal conductivity (k_{ef}) and their analysis, they are in most cases smoothed out as follows [3].

The thermal conductivity of He II in channels that are closed on one side, the closed ends of which were heated, was measured in heat-transfer processes, under conditions where the total mass flux of helium was zero. In such conditions, on the basis of a two-liquid model, a flow such that the superfluid component moves to the heater and the normal component issues from the channel is proposed. The amount of heat transferred in this way is equal to the product of the total specific entropy of the liquid at the given temperature and the absolute temperature. The resistance to the flow in the ideal case must be completely determined by the friction arising in the motion of the normal component. Additions to this ideal model are known (e.g., the Gorter–Mellink correction), but they will not be employed here, because they would hinder the achievement of the basic aim of qualitative analysis: the elucidation of the main motive forces and the basic tendencies in developing a model of the process.

On the basis of considering the above-noted ideal-model assumptions, as well as the equations determining the resistance in laminar flow of the normal component and the thermomechanical pressure, that is, the upward force arising in the thermomechanical effect in He II, an expression was obtained for the thermal resistance of the He-II column:

$$\frac{\Delta T}{Q}=\frac{1}{G}\frac{\eta_n}{\rho_s^2 S^2 T}. \tag{4}$$

It should be emphasized that in Eq. (4) there is nothing at all that would characterize the heat transfer at the liquid–solid boundary in any way. Equation (4) determines the possibility and rate of heat flow from the heated surface. This equation (and the approach itself) may obviously be valid in the case when the thermal resistance at the solid–liquid interface has no influence on the total heat transfer. This remark is especially important for heated channels where the motion of the normal component occurs partially and sometimes mainly on account of natural convection. In the considered range of parameters, the bulk-expansion coefficient of helium II $\beta < 0$ [2, 3]. In connection with this, the density of the normal component of He II (ρ_n) increases on heating, which means that downward motion of the normal component over the channel height must be ensured.

The thermal resistance of the heated cylindrical channel with He II may be written approximately as follows, in general form

$$\frac{1}{K}=\frac{1}{\alpha_0}+\frac{1}{v\rho c_p}\frac{4l}{d}. \tag{5}$$

It is known that in sealed channels [4], q_{cr} (or K) is practically an order of magnitude smaller than the values obtained for a large volume. Since this may only be explained from the perspective of the possibility of heat removal from the heated body, it is expedient to focus attention on the form of the model of the process where

$$\frac{1}{K}\sim\frac{1}{v\rho c_p}\frac{4l}{d}. \tag{6}$$

Thus, the heat-transfer crisis (attainment of q_{cr}) is seen to occur when the limiting permissible rate of heat transfer from the heated channel is reached. This leads to the creation of a region with elevated He–II temperature, heating of the wall above T_λ, and the formation of a vapor phase. (As shown by the present experiments, the dependence $\alpha_0 = f(T)$ remains quantitatively the same right up to the critical heat-flux density.) The appearance of vapor phase fundamentally alters the whole character of the interaction as considered on the basis of the two-liquid model, and leads to significant change in the whole heat-transfer mechanism.

For the case of steady conditions ($T = \mathrm{const}$, $v\rho = \mathrm{const}$), in accordance with the above-noted considerations, the following premises may be adopted (including the condition of laminar motion of the normal component)

$$\rho_s v_s = \rho_n v_n,\ q=\rho_s v_s S T,\ v_n=\frac{G}{\eta_n}\Delta P. \tag{7}$$

Note that, instead of the last of these expressions, the dependence for turbulent conditions of flow (e.g., in the form of the Blasius or Nikuradze equations) could be considered. However, at the stage of preliminary analysis, this is inexpedient.

The available pressure drop determining the evacuation rate of the normal component consists, as follows from the two-liquid model adopted, of two parts

$$\Delta P=\Delta P_1+\Delta P_2, \tag{8}$$

where ΔP_1 is the pressure drop determined by the bulk expansion of the liquid and also the channel geometry. Thus, for an inclined channel

$$\Delta P_1=\beta\Delta T l \sin\varphi. \tag{9}$$

The dependence for ΔP_1 takes a more complex form for a horizontal channel. Also

$$\Delta P_2=\rho S\Delta T. \tag{10}$$

This is the pressure drop determined by the thermomechanical effect. It is appropriate to note here that a number of authors [5] have considered the action of a hydrostatic liquid column in taking the temperature difference in a large volume of helium II into account. However, as shown by the results of the experiments in [1], this is not necessary for an open, uniformly heated channel.

It follows from Eqs. (7)–(10) that

$$q_{cr} = G\frac{\rho_s ST}{\eta_n}(\Delta P_1 + \Delta P_2). \tag{11}$$

Note that a dependence of similar form was obtained in [3, 6] for channels with adiabatic walls, the sealed ends of which are heated. However, they were not compared with experimental results.

Analysis of the parameters appearing in Eq. (11) shows that analysis of the experimental data may be conducted in the form

$$q_{cr} = f\left(\frac{\rho_s^2 S^2 T}{\eta_n};\ \frac{l}{d};\ \sin\varphi\right). \tag{12}$$

The dependence of the complex $\rho_s^2 S^2 T/\eta_n$ on the He-II temperature is shown in Fig. 1. It is clearly seen that the maximum of this curve is in the region $T \simeq 1.9°K$. It is also necessary to note that this temperature range also corresponds to a maximum (although considerably less expressed) of the second sound velocity in He II [3] – oscillations of the relative densities of the normal and superfluid components. The character of the given dependences is in good agreement with the published data on q_{cr} and k_{ef} in a large volume and sealed channels with He II.

In generalized form, all the results obtained on the critical heat-flux density in uniformly heated open channels of cylindrical form cooled by helium II, in the temperature range 1.7-2.1°K [1], may be generalized by the dependence

$$q_{cr} = 2\cdot 10^{-16}\frac{\rho_s^2 S^2 T}{\eta_n}\exp(\sin\varphi + 11.7)\left(\frac{l}{d}\right)^{-1.5},\ \frac{W}{m^2}. \tag{13}$$

Analysis of the experimental data obtained is shown in Fig. 2. The deviation of the experimental values of q_{cr} from the values given by calculations from Eq. (13) lies within limits of ±30%.

NOTATION

T, liquid temperature in bath, °K; T_λ, temperature corresponding to the λ point, °K; Q, heat flux, W; q, heat-flux density, W/m²; q_{cr}, critical heat-flux density, W/m²; ΔT, temperature difference, °K; α_0, heat-transfer coefficient at the solid–liquid (helium II) boundary, W/m²·°K; K, heat-transfer coefficient in the channel, W/m²·°K; S, entropy, J/kg·°K; v, v_s, v_n, velocity of total, superfluid, and normal components, m/sec; ρ, ρ_s, ρ_n, density of total, superfluid, and normal components, kg/m³; k_{ef}, effective thermal conductivity of helium II, W/m·°K; η_n, viscosity of normal component, Pa·sec; c_p, specific heat, J/kg; G, Poiseuille's number; d, internal diameter of channel, m; l, channel length, m; φ, angle of slope of channel with respect to horizontal, deg; σ_B, parameter depending on the specific properties of the liquid and the solid; k_b, Boltzmann constant; h, Planck constant; ρ_S, density of solid, kg/m³; w_F, first sound velocity in liquid helium, m/sec; w_t, w_l, velocity of longitudinal and transverse propagation of sound in the solid, m/sec; $F(W_t/w_l)$, function of elastic constants of the solid.

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