ESTIMATION OF THE EXTREMAL VALUES OF THE CRITICAL HEAT INPUT IN THE NUCLEATE BOILING OF HELIUM IN A CENTRIFUGAL FORCE FIELD

Yu. A. Kirichenko and K. V. Rusanov UDC 536.248.2.001.5

Models are proposed, and equations are derived for estimating the maximum (at $\phi = 0°$) and minimum (at $\phi = 180°$) values of the first critical heat flux under the conditions of large centrifugal accelerations.

Investigations of the boiling of helium in spinning cryostats at the Physicotechnical Institute of Low Temperatures of the Academy of Sciences of the Ukrainian SSR have disclosed "anomalous" dependences of the first critical ("first-stage burnout") heat flux density q_{cr} on the relative inertial acceleration (number of g's) $\eta = g/g_n$ and on the angle of rotation ϕ of the heater [1-4]. Here we submit approximate interpretations of these effects.

In the case of a sufficiently large number of g's $\eta \geq \eta^*$ and $\phi = 0°$, the quantity q_{cr} is practically independent of the inertial force proper (i.e., the force determined by the pressure and supercooling) [1-3]; for $\eta < \eta^*$ the function $q_{cr}(\eta)$ is close to its form deduced from the relations of the hydrodynamic theory of burnout phenomena, e.g., from the equation of S. S. Kutateladze:

$$q_{cr} = KL\sqrt{\rho_v}\sqrt[4]{\sigma g_n \eta (\rho - \rho_v)}, \quad (1)$$

where $q_{cr} \sim \eta^{0.25}$.

Figure 1 shows the experimental values of q_{cr} for the boiling of helium in a centrifugal force field at various levels h of the liquid above the heater [2, 4]. The heat-transfer surface was the end face of a copper cylinder of diameter 15 mm and thickness 5 mm. It is evident in the example of h = 10 mm (curve 4) that the values of q_{cr} calculated according to Eq. (1) exceed the experimental values, beginning with $\eta = \eta^* \approx 400$. To obtain the pure functional dependence $q_{cr}(\eta)$, corrections for the increase of the pressure and the supercooling in the centrifugal force field were introduced in the experimental data according to the procedure of [1]. The "pure" (relative) dependence of the first critical heat flux $\tilde{q}_{cr} = q_{cr}(\eta)/q_{cr}(\eta = 1)$ on the number of g's is shown in Fig. 2; we see that $\tilde{q}_{cr} \approx$ const (or decreases slightly with increasing η) for $\eta \geqslant 300 \pm 100$. The near invariance of the "pure" dependence of q_{cr} on η has also been observed in the boiling of nitrogen in a centrifugal force field [5] and in the motion of boiling water through ducts [6, 7], where high relative centrifugal accelerations were achieved by swirling. We note that the number of g's η^* at which the maximum (limiting) critical heat flux $q_{cr} = q_{cr}^*$ is attained increases with the critical pressure p_c of the investigated liquid approximately as $\eta^* \sim p_c^{1/3}$.

Alternative interpretations can be given for the fact that q_{cr} is constant at $\eta > \eta^*$ (or as $\eta \to \infty$). Labuntsov and Soziev [6] attribute the upper limit of q_{cr} to the fact that the heat-transfer surface attains the limiting superheat of the liquid or that the liquid interlayer between the surface and the bubbles attains the minimum possible thickness. However, this approach can provide only a very crude estimate of q_{cr}^*. Motivated by previous investigations [2, 5], Kutateladze et al. [8] explain the upper limit of q_{cr} by the influence of the Coriolis forces on the vapor phase. The relation obtained for $\eta \to \infty$ in this case gives a strong dependence of q_{cr}^* on the geometrical parameters of the experiment, which has yet to be confirmed experimentally.

We intend to explain the behavior of q_{cr} in the boiling of helium in a centrifugal force field without the limitations of the above-mentioned interpretations. Two experimental facts [2, 4] are taken into consideration in the ensuing derivation. The first fact is the near invariance of the heat-transfer coefficient for $\eta > \eta^*$ and $q \approx q_{cr}$, and the second is the presence of centers of film boiling together with nucleate boiling on the heat-transfer

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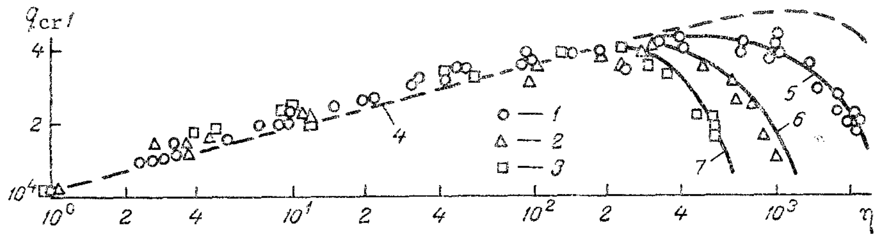

Fig. 1. Critical heat flux q_{cr1}, W/m², vs number of g's in the boiling of helium. 1-3) Experimental data [2, 4]: 1) h = 10 mm; 2) 72; 3) 185; 4) calculated according to Eq. (1); 5-7) calculated according to Eq. (5); 5) h = 10 mm; 6) 72; 7) 185.

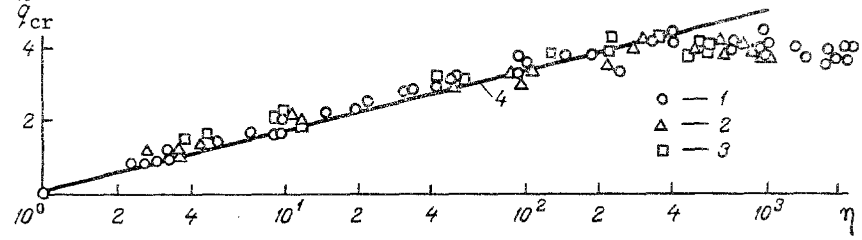

Fig. 2. "Pure" dependence of the critical heat flux on the number of g's in the boiling of helium. 1-3) see Fig. 1; 4) $\tilde{q}_{cr} = \eta^{0.25}$.

surface. The critical temperature differences ΔT_{cr} in every case are much greater than the limiting superheat ΔT_{lim} ($\Delta T_{cr} \approx 1$°K at $q \approx 10^4$ W/m², and $\Delta T_{cr} \gtrsim 2$°K at $q \approx 4\cdot10^4$ W/cm²); the relative area δS_f of the heat-transfer surface occupied by film-boiling centers increases with the value of η and can attain 30-40% at η ≈1000-2000 [3]. The value η* corresponds to $\delta S_f \approx 20\%$ and a pressure of $(1.3 \pm 0.1)\cdot 10^5$ Pa. A certain part of the total temperature difference $\Delta T = T_H - T_s$ (T_H is the temperature of the heat-transfer surface, and T_s is the saturation temperature) is possibly equal to the Kapitza temperature jump ΔT_K, which also occurs in the boiling of helium I [9]; in this case, evidently, $\Delta T_K \ll \Delta T$. Large temperature differences ($\Delta T > \Delta T_{lim}$) in the boiling of helium on flat copper heaters have also been observed in the case η = 1 for heaters having a sufficiently small thickness δ_H. At $q \approx 10^4$ W/m², e.g., the value $\Delta T \approx 2$°K has been obtained [10] for $\delta_H = 0.12$ mm, but $\Delta T \approx 0.4$°K for $\delta_H = 17.4$ mm. Since the Kapitza temperature jump does not depend on the sample thickness, it is obvious that the value of ΔT_K must be considerably smaller than 0.4; apparently $\Delta T_K \leq$ 0.1-0.2°K, judging from the average experimental data on the transient heating of helium I [9].

The analysis of Helmholtz instability (loss of hydrodynamic stability of a system consisting of ascending vapor columns of diameter D and, between them, liquid jets descending toward the heat-transfer surface) is known to comprise an essential component of the hydrodynamic burnout model. The spacing of the vapor columns is equal (or proportional) to the critical wavelength of the disturbance

$$\Lambda = 2\pi\sqrt{\sigma/g_n\eta(\rho-\rho_v)}. \tag{2}$$

Let us assume that a large fraction of the surface is blanketed with vapor under the conditions of large centrifugal accelerations and that conglomerates of bubbles (with a "dry spot" at their base) break away from the surface in accordance with the same laws as for ordinary vapor bubbles in the dynamic breakoff regime [3]:

$$D_d^* = C_D^* \beta^{*4/3} (g_n\eta)^{-1/3}, \tag{3}$$

where the growth modulus β* is given by an equation of the Plesset–Zwick type

$$\beta^* = C_\beta \lambda \Delta T / L\rho_v \sqrt{a}. \tag{4}$$

Let us assume next that $D = D_d^*$ in the preburnout situation. The quantity D_d^* decreases more slowly than Λ with increasing number of g's, and it increases with the heat flux q. Suppose that $D_d^* \geq \Lambda$ at $\eta < \eta^*$ for any value of q and that the burnout process is hydrodynamic in nature. Then the validity of the hydrodynamic burnout model is limited by the condition $D_d^* \geq \Lambda$, which corres-

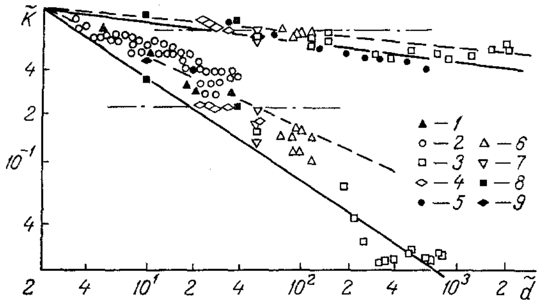

Fig. 3. Ratio $\tilde{K}$ vs relative diameter $\tilde{d}$. Experimental: 1) data of [15] (water, $\eta > 1$); 2) [14] (ethanol, $\eta = 1$); 3) [2-4] (helium, $\eta > 1$); 4) [12] (helium, $\eta = 1$); 5) [20] (helium, $\eta = 1$); 6) [3] (helium, $\eta = 1$); 7) [13] (helium $\eta = 1$); 8) nitrogen, our data ($\eta = 1$); 9) [21] (nitrogen, $\eta = 1$). Calculated: according to Eqs. (11) and (12) with $m = \ln\sqrt{(190° - \phi)/190°}/\ln 25$ (dashed lines); according to Eq. (6) (dot-dash lines). The upper and lower groups of data correspond to $\phi = 90°$ and 180°.

ponds to $\eta \geq \eta^*$ and $q \equiv q_{cr}$; burnout sets in here as a result of consolidation of the vapor conglomerates on the heat-transfer surface. Substituting $\Delta T = q/\alpha^*$ in Eq. (4) and then substituting Eq. (4) in (3), we infer from the condition $D_d^* = \Lambda$ that for $\eta \geq \eta^*$

$$q_{cr} = C_q \alpha^* \frac{L\rho_v \sqrt{a}}{\lambda} \sqrt[8]{\sigma^3/g_n \eta (\rho - \rho_v)^3}, \tag{5}$$

where $C_q = (2\pi)^{3/4}/C_\beta^* C_D^{*3/4}$.

Assuming that $\alpha^* \approx 1.3 \cdot 10^4$ W/m²·K for the boiling of helium [2, 4] and determining C_q from a comparison of the calculated and experimental (see Fig. 1) values of q_{cr} at relative accelerations η^* around which a deviation from the hydrodynamic burnout model sets in ($\eta^* \approx$ 230, 300, 400 for h = 185, 71, 10 mm), we obtain $C_q \approx 0.52 \pm 0.03$. The results of calculations according to Eq. (5) are shown in Fig. 1. The functions $q_{cr}(\eta)$ calculated according to Eq. (5) for $\eta > \eta^*$ agree with the approximate experimental curves [4].

Assuming that the coefficient in Eq. (4) is the same as in the growth of ordinary bubbles, i.e., that $C_\beta^* = C_\beta \approx 2$, we obtain $C_D^* \approx 6$. Since $C_D \approx 2$ for these bubbles [3], the implication is that the postulated bubble conglomerates occupy an order-of-magnitude greater area than ordinary bubbles.

The investigated case of boiling at $\eta \geq \eta^*$ corresponds to a certain intermediate regime, where nucleate and film boiling regimes coexist on the heat-transfer surface with respective space scales D_d^* and Λ. A boiling regime with a smaller space scale occurs under these conditions. First-stage burnout can be treated as the transition from the domain of the parameters with $D_d^* < \Lambda$ (predominantly nucleate boiling) to the domain with $D_d^* > \Lambda$ (film boiling).

The influence of the angle ϕ on q_{cr} is usually estimated according to Vishnev's equation [11], which can be represented in the form

$$q_{cr}(\varphi) = q_{cr}(0°) \sqrt{(190° - \varphi)/190°}, \tag{6}$$

where $q_{cr}(0°)$ is calculated according to relation (1).

Equation (6) was derived on the basis of the processing of experimental data primarily on the boiling of helium on heaters of diameter d_H = 10-30 mm [12, 13]. According to Eq. (6), the ratio $q_{cr}(\phi)/q_{cr}(0°)$ does not depend on the heater dimensions, the pressure, or the acceleration g (according to Vishnev [11], for η = 1-2500).

Subsequent investigations have shown, however, that the value of q_{cr} on a down-turned surface ($\phi = 180°$) depends on the heater diameter d_H, and the ratio $q_{cr}(180°)/q_{cr}(0°)$ decreases with an increase in d_H or $\tilde{d} = d_H/b = d_H\sqrt{g_n \eta(\rho - \rho_v)/\sigma}$ [14]: from unity at $\tilde{d} = 2$ to 0.2 at $\tilde{d} = 60$. The experiments show that this ratio also depends significantly on the number of g's. When helium boils in a centrifugal force field on a heater with d_H = 15 mm, the quantity $q_{cr}(180°)$ decreases as η is increased [2, 3], and for η = 100-200 the ratio q_{cr}

$(180°)/q_{cr}(0°)$ assumes a value of approximately 0.02 instead of the value 0.23 obtained in calculations according to Eq. (6).

We note that a similar result has been obtained earlier [15] in a narrower range of relative accelerations for the boiling of water; the results of [15] are given in [11], but they are not properly taken into account in the derivation of Eq. (6). The decrease of q_{cr} with increasing η has also been noted in the boiling of helium on the generatrix of a paraxial circular duct close to the axis of revolution [16] and on the surface of a cylinder rotating in a liquid [17]. The centrifugal forces in both cases "detach" the liquid from the heat-transfer surface, promoting the onset of burnout.

The function $q_{cr}(\tilde{d})$ for $\phi = 180°$ can be interpreted qualitatively as follows. Large bubbles (vapor film) are formed on a down-turned surface in the preburnout situation and then ascend under the action of the heater. We assume that the condition for the onset of burnout is equality of the rate of formation of the film w and the rate of ascension of the bubbles u. The rate of formation of the vapor film is

$$w \sim \frac{q}{L\rho_v}\frac{d_H}{\delta_f} \sim \frac{q}{L\rho_v}\frac{d_H}{2b}, \tag{7}$$

where the film thickness $\delta_f \approx 2b$ [18].

The rate of ascension of the large bubbles is [19]

$$u \sim \sqrt{Rg_n\eta(g-g_n)/\rho}. \tag{8}$$

The volume of the bubbles is proportional to bd_H^2, and so their average radius is

$$R \sim \sqrt[3]{bd_H^2}. \tag{9}$$

Substituting Eq. (9) in (8), we obtain from the condition w = u

$$q_{cr}(180°) = C\frac{L\rho_v}{\sqrt{\rho}}\sqrt[4]{\sigma g_n\eta(\rho-\rho_v)}\left(\frac{2b}{d_H}\right)^{2/3}, \tag{10}$$

where C is a proportionality factor, which can also depend on the pressure.

Assuming that Eq. (1) holds with $K = K_\infty \approx 0.15$ and $C\sqrt{\rho_v}/K_\infty\sqrt{\rho} \approx 1$ for $\phi = 0°$ and a sufficiently large heater diameter, we obtain from Eqs. (1) and (10)

$$\tilde{q}_{cr}(180°) = K(180°)/K_\infty = (\tilde{d}/2)^{-2/3}. \tag{11}$$

The results of calculations according to Eq. (11) are compared with the existing experimental data, including those obtained in a centrifugal force field, in Fig. 3 (solid line and lower group of points). We see that the lower bound of the possible experimental values is determined according to Eq. (11); the approximation (6) is valid only for $\tilde{d} \approx 30 \pm 20$. Consequently, Eq. (11) satisfactorily approximates the very low values of $q_{cr}(180°)$ obtained in [2] and they are attributable to the very large values of $\tilde{d}$; the calculations according to Eq. (6) exhibit an order-of-magnitude divergence in comparison with the experimental data.

The function $q_{cr}(\tilde{d})$ also holds for $\phi = 90°$ (see the upper group of points in Fig. 3). The following generalization of Eq. (11) can be proposed for an arbitrary orientation angle:

$$\tilde{q}_{cr}(\varphi) = \tilde{K}(\varphi) = (\tilde{d}/2)^m, \tag{12}$$

where $\tilde{q}_{cr}(\phi) = q_{cr}(\phi)/q_{cr}(0°)$; $\tilde{K}(\phi) = K(\phi)/K_\infty$; $m = \ln\sqrt{(185°-\phi)/185°}/\ln 15$.

A comparison of the calculations according to Eq. (12) with the experimental data (Fig. 3) indicates satisfactory agreement. Better agreement with the experimental values is given by Eq. (12) for $m = \ln\sqrt{(190°-\phi)/190°}/\ln 25$; for $\tilde{d} = 50$ it goes over to Eq. (6).

NOTATION

a, thermal diffusivity of the liquid, m^2/sec; $g_n = 9.81$ m/sec^2; K, stability criterion; L, heat of vaporization, J/kg; λ, thermal conductivity of the liquid, W/m·K; ρ, ρ_v, densities of the liquid and the vapor, kg/m^3; σ, coefficient of surface tension, N/m.

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PHASE EQUILIBRIA AND METASTABLE STATES

V. P. Skripov

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Agreement is remarked between the theory of homogeneous seed-formation and tests on the kinetics of the boiling and crystallization of fluids. The continuation of the two-phase equilibrium line into the domain where both phases are metastable is discussed. The application of thermodynamic similarity to describe the melting of substances is shown.

1. The phase equilibrium condition in a one-component system

$$\mu_\alpha(T,\ P) = \mu_\beta(T,\ P) \tag{1}$$

refers to a plane interface

$$\mu = u - Ts + Pv. \tag{2}$$

A part of the surface of the chemical potential μ which proceeds higher than the μ of the competing phase behind the line of intersection (1) corresponds to phase metastable states. Small amplitude perturbations in the metastable phase (density fluctuations, say) are resorbed if the spinodal is not reached, for which we have

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