CRITICAL HEAT-TRANSFER CHARACTERISTICS FOR THE BOILING OF HELIUM I IN A CENTRIFUGAL FORCE FIELD

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The critical heat fluxes and critical differential temperatures associated with the boiling of helium in a centrifugal force field on a flat copper heater are investigated in the range of relative accelerations 1-2280.

The timeliness of heat-transfer studies in helium in a centrifugal force field is dictated by the considerable promise of developments in superconducting machines and devices [1]. For the analysis of the cooling system for a rotor equipped with a superconducting field coil it is necessary to know the characteristics of the boiling of helium under the conditions of large relative inertial accelerations $\eta = g/g_n$. Of special significance in this connection is the determination of the upper limit of the nucleate boiling regime, because the transition to film boiling can cause overheating of the coil and departure from the superconducting state.

The few papers published on the critical heat-transfer characteristics of the boiling of helium I in a field of centrifugal forces report studies in the ranges $\eta \leq 179$ [2, 3] and $\eta \leq 126$ [4], i.e., for values far below those realized in the rotor cooling systems of superconducting oscillators. The results of studies of high-boiling liquids at sufficiently high relative acclerations [5, 6] cannot be used, without suitable testing, to analyze the heat-transfer process in helium. These studies have been carried out at much lower reduced pressures than those at which helium exists in rotating cooling systems. An urgent need therefore exists for the investigation of the critical heat-transfer characteristics associated with the boiling of helium I at relative accelerations far exceeding those actually attained, i.e., $\eta \gg 10^2$.

Here we report a study of the characteristics of the first and second critical points for the boiling of helium (critical heat fluxes q_{cr1} and q_{cr2} and the corresponding critical differential temperatures ΔT_{cr1} and ΔT_{cr2}).

The investigations were carried out on a special centrifuge (Fig. 1) consisting of two main assemblies: the stator 1 and a rotor with a vertical axis of rotation. The hollow shaft 2 of the rotor is packed in rubber seals 3. Two working chambers 5 are mounted diametrically opposite one another on the center block 4. Each working chamber is thermally insulated by the vacuum shield 6 and the protective dewar 7. A constant influx of liquid helium into the working chambers is supplied through the stationary siphon tube 8, which is connected to the rotating siphon tube 9. The liquid level is held constant in the working volume (10 mm above the heat-transfer surface of the heater 10) by draining off its excesses through the overflow tube 11.

The heat-transfer surface is the end of a copper cylinder with a diameter of 15 mm, finished to purity class 11 (GOST-2789-73).

The temperature of the heat-transfer surface of the heater as well as the temperatures of the liquid and the vapor in the working volume were determined with germanium resistance thermometers within 0.02°K error limits. The electrical signals from the temperature sensors were sent to the stationary instrumentation by means of a special slip-ring assembly. Electrical power is supplied to the heater in the working volume through a power contacting device.

The increment Δp of the hydrostatic pressure of the liquid and vapor in the centrifugal forces ($0 \leq \Delta p < 8.2 \cdot 10^4$ Pa) is taken into account in calculating the pressure at the heat-transfer surface.

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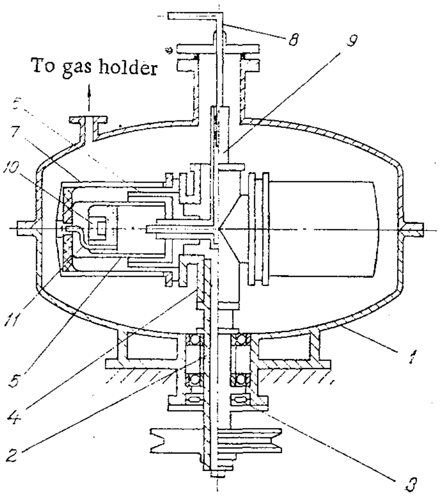

Fig. 1. Experimental apparatus.

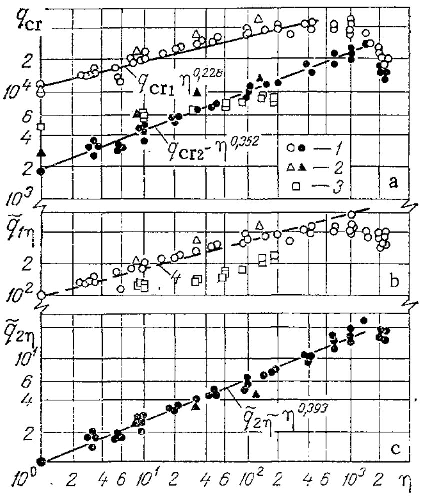

Fig. 2

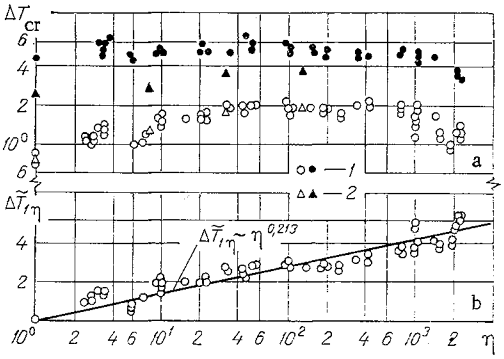

Fig. 3

Fig. 2. Critical heat fluxes q_{cr1} (light points) and q_{cr2} (dark points), W/m^2, versus relative acceleration for heater orientation $\varphi_\omega = 0$. a) Experimental dependence of q_{cr} on η; b) "pure" dependence of the reduced first critical heat flux; c) "pure" dependence of the second critical heat flux on the relative acceleration; 1) flat copper heater, data of this study; 2) flat copper heater, data of [4]; 3) tubular stainless steel heater, data of [2]; 4) Kutateladze function $\tilde{q}_{1\eta} = \eta^{0.25}$.

Fig. 3. Critical differential temperatures ΔT_{cr1} (light points) and ΔT_{cr2} (dark points), °K, versus relative acceleration for heater orientation $\varphi_\omega = 0$. a) Experimental dependence of ΔT_{cr} on η; b) "pure" dependence of the reduced first differential temperature; 1) data of this study; 2) data of [4].

The experiments were carried out for three different orientations of the heater relative to the centrifugal acceleration vector (i.e., different angles φ_ω between the centrifugal acceleration vector and the outward normal vector to the heat-transfer surface): a) orientation I: heat-transfer surface facing the axis of rotation ($\varphi_\omega = 0$), distance of the heat-transfer surface from the axis of rotation r = 301 mm, thickness of the liquid layer above the heater h = 10 mm, relative-acceleration range η = 1–2280; b) orientation II: heat-transfer surface parallel to the radius of rotation ($\varphi_\omega = 90°$), r = 300 mm, h = 9.5 mm (measured to the center of the heat-transfer surface), η = 1–1185; c) orientation III: heat-transfer surface facing away from the axis of rotation ($\varphi_\omega = 180°$), r = 312 mm, h = 21 mm, η = 1–250.

The results of the experimental study of the critical heat fluxes for the case of orientation I ($\varphi_\omega = 0$) are shown in Fig. 2a for various relative accelerations. The variation of q_{cr1} and q_{cr2} as the relative acceleration

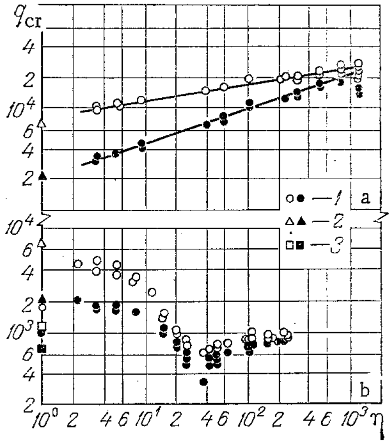

Fig. 4. Critical heat fluxes q_{cr1} (light points) and q_{cr2} (dark points), W/m², versus relative acceleration for different heater orientations. a) Orientation II, $\varphi_\omega = 90°$; b) orientation III, $\varphi_\omega = 180°$; 1) data of this study; 2) [7] ($\eta = 1$), $\varphi = 90°$; 3) [7] ($\eta = 1$), $\varphi = 180°$.

is increased exhibits a nonmonotonic behavior. The functions $q_{cr1}(\eta)$ and $q_{cr2}(\eta)$ are determined both by the influence of the relative acceleration per se and by the increase of the hydrostatic pressure of the liquid and vapor column at the surface of the heater.

Approximating the experimental data (Fig. 2a) in the intervals of monotonic growth of the critical heat fluxes by the least-squares principle in accordance with the equation

$$q_{cr1,2} = A_{1,2}\eta^{k_{1,2}} \tag{1}$$

for q_{cr1} we obtain $A_1 = (1.14 \pm 0.03) \cdot 10^4$ W/m², $k_1 = 0.228 \pm 0.007$ ($1 \le \eta < 1500$) (the rms deviations are indicated).

On the other hand, the ratio of these quantities $C_q(\eta) = q_{cr2}(\eta)/q_{cr1}(\eta)$ should not depend on the increment of the hydrostatic pressure, because the pressure variations of q_{cr1} and q_{cr2} are approximately identical [7]. It is evident from Fig. 2a that the quantity $C_q(\eta)$ increases with the relative acceleration, varying roughly from 0.17 to 0.75 as the relative acceleration is increased from 1 to 2200. This behavior corresponds to a stronger dependence for $q_{cr2}(\eta)$ in comparison with $q_{cr1}(\eta)$ for the intervals of monotonic growth of the critical heat fluxes, as has been observed in the case of noncryogenic liquids in [8].

To determine the influence of the actual relative acceleration on q_{cr1} (i.e., to find the "pure" dependence of q_{cr} on η) we use the procedure proposed in [6]. The dependence of q_{cr} on the relative acceleration η and the pressure increment Δp is written in the form

$$q_{cr}(\eta, \Delta p) = q_{cr}(1, 0)\,\tilde{q}_\eta\,\tilde{q}_p, \tag{2}$$

where $q_{cr}(1, 0)$ is the value of the critical heat flux under steady-state conditions ($\eta = 1$) at atmospheric pressure ($\Delta p = 0$); $\tilde{q}_p$ is the variation of q_{cr} under steady-state conditions with an increase in the pressure:

$$\tilde{q}_p = \frac{q_{cr}(1, \Delta p)}{q_{cr}(1, 0)}; \tag{3}$$

and $\tilde{q}_\eta$ is the sought-after variation of q_{cr} for a constant pressure ($\Delta p = 0$) and an increase in the relative acceleration:

$$\tilde{q}_\eta = \frac{q_{cr}(\eta, 0)}{q_{cr}(1, 0)} = \frac{q_{cr}(\eta, \Delta p)}{q_{cr}(1, 0)\,\tilde{q}_p} = \eta^k. \tag{4}$$

We determine $\tilde{q}_p$ according to the data obtained in [7] on a copper heater.

We have confirmed experimentally the virtual absence of subcooling of the liquid for heat fluxes close to the critical values, making it unnecessary to introduce a correction for subcooling (proposed in [6]).

Figures 2b and 2c show the experimental data after reduction according to (4), i.e., the relative critical heat fluxes corrected for the variation of q_{cr} due to growth of the hydrostatic pressure.

The results shown in Figs. 2b and 2c indicate that the experimental functions q_{cr1} (η) and q_{cr2} (η) remain nonmonotonic even after the pressure correction, i.e., this nonmonotonicity is not caused by the influence of the pressure, but solely by the influence of the relative acceleration. It is conceivable that the function q_{cr} (η) will differ for different reduced pressures.

The dashed line in Fig. 2b represents the function $\tilde{q}_{\eta}$ (η) obtained from the hydrodynamical theory of critical points [9]: $\tilde{q}_{1\eta} = \eta^{0.25}$. In the interval $1 \leq \eta < 1000$ it approximates with satisfactory accuracy the relative values of the first critical heat flux obtained in this study. The maximum deviations of the points from the line 4 in Fig. 2b do not exceed 32%. The values of $\tilde{q}_{1\eta} = q_{cr1}(\eta)/q_{cr1}(1)$ fall between the data of [2] and [4].

The "pure" dependence for the second critical heat flux in the interval $1 \leq \eta < 1500$ is approximated by the following equation obtained by the least-squares principle: $\tilde{q}_{2\eta} = \eta^{k_2}$, where $k_2 = 0.393 \pm 0.007$ (Fig. 2c).

The nonmonotonicity of the "pure" functions $q_{cr1}(\eta)$ and $q_{cr2}(\eta)$ at sufficiently high relative accelerations and the stronger dependence of $q_{cr2}(\eta)$ in comparison with $q_{cr1}(\eta)$ cannot be explained within the scope of the hydrodynamic model of the critical points for boiling regimes. The critical point in this case is possibly of a thermodynamic nature [although the thermodynamic model of the critical points also fails to account for the confirmed behavior of $q_{cr}(\eta)$]. Here the temperature of the heat surface T_H must attain maximum possible superheats of the liquid T_{ms}. In fact, the experimentally determined values of T_H not only exceed T_{ms}, but also the critical temperature T_c.

Figure 3a shows the values of the critical differential temperatures ΔT_{cr} for orientation I. The values of the differential temperatures ΔT are determined in the form $\Delta T = T_H - T_{SH}$, where T_{SH} is the liquid saturation temperature corresponding to the pressure at the heater. The values of ΔT_{cr1} obtained in [4] are in good agreement with the data of this study. The behavior of ΔT_{cr} with variation of the relative acceleration is analogous to the function $q_{cr}(\eta)$; for $\eta > 1000$ both ΔT_{cr1} and ΔT_{cr2} are observed to decrease, and their values tend somewhat to converge as the relative acceleration is increased.

We have attempted to determine the "pure" dependence of ΔT_{cr1} on the relative acceleration by analogy with the case of $\tilde{q}_{\eta}$:

$$\Delta\tilde{T}_{1\eta} = \frac{\Delta T_{cr1}(\eta,\ 0)}{\Delta T_{cr1}(1,\ 0)} = \left(\frac{\Delta T_{cr1}(\eta,\ \Delta p)}{\Delta T_{cr1}(1,\ 0)}\right) \Big/ \left(\frac{\Delta T_{cr1}(1,\ \Delta p)}{\Delta T_{cr1}(1,\ 0)}\right) = \eta^{l}. \tag{5}$$

The values of ΔT_{cr1} (1, Δp) are obtained by means of the equation

$$\Delta T_{cr1}(1,\ \Delta p) = B(1 - T_{SH}/T_C)^{7/6}, \tag{6}$$

in which B = 3.3°K. Equation (6), which was postulated in [10], satisfactorily generalizes the results of various authors on heat transfer in helium. Least-squares processing of the experimental data according to expression (5) yields in the investigated range of relative accelerations $\eta = 0.213 \pm 0.004$. The large values of ΔT_{cr1} obtained in this study and in [4] for the boiling of helium at large relative accelerations can be attributed to the fact that even before the onset of the first critical point of heat transfer stable seats of film boiling are formed on the heating surface, coexisting there with the nucleate boiling process on the rest of the surface. The mean surface temperature (recorded with a thermometer) is determined by the ratio of the areas occupied by nucleate and film boiling and can greatly exceed the surface temperature for nucleate boiling. As the heat flux is increased the fraction of the surface occupied by film boiling increases, and its mean temperature can exceed the critical (thermodynamic) temperature well before the onset of the critical heat-transfer point over the entire surface (in this study the temperature of the heater surface at the onset of the first critical point attained 6.4°K).

This kind of process has been observed in the boiling of helium on a stainless steel heater under steady-state conditions ($\eta = 1$) [11]. Here ΔT_{cr1} attained values of 6-11°K (in this study and in [4] $\Delta T_{cr1} \approx 1$-2°K). In [11] it was possible for the emerging seats of film boiling to persist owing to the poor thermal conductivity of the heater material. In the case of boiling at high relative accelerations the preservation of the seats of film boiling is promoted by the relatively large heat-transfer coefficients associated with film boiling.

We have investigated the influence of the orientation of the heat-transfer surface on the critical heat flux. In the case of orientation II ($\varphi_{\omega} = 90°$) the dependence of q_{cr2} on η is practically invariant in comparison with the dependence for $\varphi_{\omega} = 0$ and can be expressed by relation (1) with $A_2 = (2.09 \pm 0.04) \cdot 10^3$ W/m^2 and $k_2 = 0.331 \pm 0.004$ in the interval of relative accelerations $2 \leq \eta < 1000$ (Fig. 4a). On the other hand, the dependence of q_{cr1}

on η for $\varphi_\omega = 90°$ is much weaker than in the case $\varphi_\omega = 0$ [in expression (1) $A_1 = (8.1 \pm 0.2) \cdot 10^3$ W/m^2, and $k_1 = 0.158 \pm 0.005$ for $2 \le \eta < 1000$]. In this orientation, as in the case $\varphi_\omega = 0$, the values of q_{cr1} and q_{cr2} tend to converge as η is increased.

Figure 4b gives data on the variation of q_{cr1} and q_{cr2} with the relative acceleration for orientation III ($\varphi_\omega = 180°$) in the interval $\eta = 2$–250. For a constant orientation of the surface relative to the centrifugal acceleration vector $\vec{a}_\omega (\varphi_\omega = 180°)$ in the interval of small relative accelerations, its orientation relative to the vector sum $\vec{g} = \vec{a}_\omega + \vec{g}_n$ will change, where $\vec{g}_n$ is the earth's gravitational acceleration. With a variation of the relative centrifugal acceleration from 1 to 20 for $\varphi_\omega = 180°$ the angle φ characterizing the position of the heater plane relative to $\vec{g}$ varies from 135 to 177°. This variation of the angle φ will necessarily decrease the value of q_{cr} by approximately 1/2.4 if we assume that this variation corresponds to the law $q_{cr1} \sim (190° - \varphi)^{1/2}$ [12]. The variation of φ for $\varphi_\omega = 0$ produces only a slight increase in the values of q_{cr1}, while in the case of orientation II ($\varphi_\omega = 90°$) the heat-transfer surface is situated in such a way that the vectors $\vec{a}_\omega$ and $\vec{g}_n$ lie in its plane and the angle φ does not depend on the relative acceleration and is equal to a constant 90°.

The variation of the real inclination of the heater surface as the relative acceleration is increased can account in large measure for the abrupt decrease of q_{cr} in the case of orientation III in the interval $1 < \eta < 20$. A decrease of q_{cr} with increasing relative acceleration has also been observed for $\eta \le 40$ in experiments with water [13]. It is evident from the data in Fig. 4b that for sufficiently large relative accelerations ($\eta > 40$) the value of q_{cr1} increases with the relative acceleration.

The nature of the variation of q_{cr2} with the relative acceleration for $\varphi_\omega = 180°$ is the same as for q_{cr1}; the function $q_{cr2}(\eta)$ has a nonmonotonic behavior with a minimum around $\eta \approx 40$. When the relative acceleration is increased to 250, the ratio q_{cr2}/q_{cr1} comes close to unity.

Also shown in Fig. 4b are the values of q_{cr} obtained under steady-state conditions ($\eta = 1$) [7] for $\varphi = 90°$ and $\varphi = 180°$. These values delimit the range of variation of $q_{cr}(\eta)$ in the interval of relative accelerations $\eta =$ 1–20.

In this study we have obtained a result that differs qualitatively from those of previous investigations, namely nonmonotonicity of the first critical heat flux as a function of the relative acceleration (of the actual relative acceleration after correction for the increase of q_{cr1} induced by the increase of the hydrostatic pressure with the relative acceleration). Clearly, this effect shows up only under the particular experimental conditions realized for the first time in this study, i.e., with the combination of high relative accelerations (of the order of 10^3) and high reduced pressures (above 0.4).

The high values of the temperature of the heating surface at the critical boiling point, exceeding the value of the critical temperature, and the function $\Delta T_{cr1}(\eta)$ must be related to the observed "anomalous" behavior of the function $q_{cr1}(\eta)$. This relationship can only be determined after the mechanism of the critical boiling point has been established; for large relative accelerations and reduced pressures it clearly cannot be described by the hydrodynamic model. This model also fails to account for the growth of the ratio q_{cr2}/q_{cr1} with the relative acceleration, as established in this study.

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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 $\Delta T/T$

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

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

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

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