EXPERIMENTAL STUDY OF THE BOUNDARY BETWEEN SINGLE-PHASE CONVECTION AND BOILING IN UNDERHEATED CRYOGENIC LIQUIDS

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The effect of pressure and underheating on the position of the boundary between heat-transfer regimes in liquid helium and hydrogen is investigated.

The nucleate boiling of cryogenic liquids is widely used in the cooling systems of modern machines and equipment. It is well known that this boiling regime is realized within a certain range of parameters (q, p, ϑ). In particular, with respect to the heat load, nucleate boiling is bordered "from below" by the regime of single-phase convection. The heat-transfer rate in these regimes is very different, so it would be useful to determine the position of the boundary separating them.

Cryogenic liquids start to boil at very low levels of superheating relative to T_s (e.g., for helium, this amounts to hundredths or even thousanths of a degree [1, 2]); the measurement of such superheats involves a certain error. The available empirical data is characterized by wide spread and cannot serve as a reliable basis for designing cooling systems. The spread is attributable partly to the probability nature of boiling.

Explaining the localization of the lower boundary of nucleate boiling is of interest for problems of storing cryogenic liquids, as well as for designing cooling systems for the windings of rotors in superconducting generators, where the underheating of the liquid is due to the action of centrifugal forces. Knowing the position of the boundary, we can determine which regime of heat transfer will occur for a given set of conditions (q, p, ϑ) and made use of the corresponding theoretical formula. It is possible that the boundary will not correspond to either the beginning or end of boiling observed experimentally.

It should be expected that the position of the boundary will depend on the direction of the transition (convection-boiling or boiling-convection). It is known that a saturated liquid begins to boil at higher heat loads q_{o1} than the loads at which boiling ceases q_{o2}: the acting center of vapor formation continues to generate vapor at a lower heat input than is required for its activation; this effect is particularly pronounced for helium [2, 3]. A similar picture can be drawn for the case of a change in underheating at q = const — the activation of the center occurs at lower values of ϑ_{o1} than the values which correspond to suppression of boiling ϑ_{o2}. Figure 1a shows the proposed character of the relation $q_o = f(\vartheta)$; in the intermediate zone the three regimes depend on the direction of the transition.

Well-known works on the subject contain only isolated information on values of (q_o, ΔT_o) in the boiling of cryogenic liquids under different conditions (p, ϑ) [1]. Data on the effect of underheating is particularly scarce. Meanwhile, it is known that an increase in the latter leads to a substantial increase in q_o [4]. In connection with this, we studied the position of the above-noted boundary for helium (at $p = (1\text{–}2)\cdot10^5$ Pa) and hydrogen (at $p = (1\text{–}6.5)\cdot10^5$ Pa) and attempted to refine the effect of the mode and direction of the regime transition.

We first evaluated the relation $q_o = f(\vartheta)$ quantitatively. The point with the coordinates (q_o, ΔT_o) corresponding to the "break" in the boiling curve (Fig. 2a) belongs to the convection section so the values of q_o and ΔT_o are related by an equation of the type [5]

$$\mathrm{Nu} = A\,\mathrm{Ra}^n \qquad (1)$$

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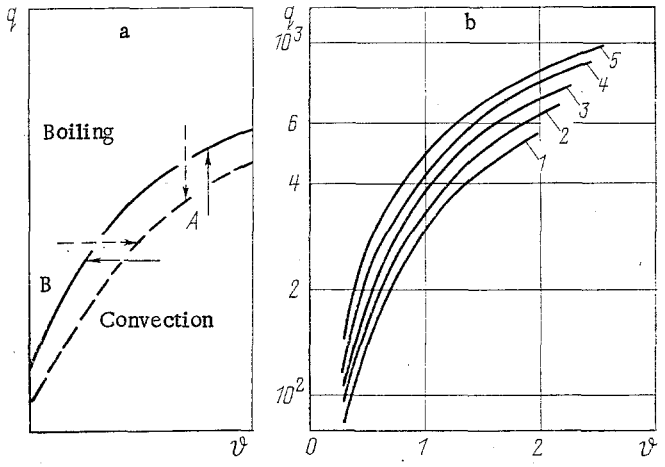

Fig. 1. Proposed form of boundary between heat-transfer regimes in the coordinates (q, ϑ): a) scheme of possible modes of transition: A) ϑ = const; b) q = const; solid line) q_{o1}; dashed line) q_{o2}; b) calculated from Eq. (1a) for helium; 1) $p = 1 \cdot 10^5$ Pa ($q_o(\vartheta = 0) = 5.23$ W/m^2); 2) $p = 1.25 \cdot 10^5$ Pa ($q_o(\vartheta = 0) = 4.08$ W/m^2); 3) $p = 1.5 \cdot 10^5$ Pa ($q_o(\vartheta = 0) = 3.42$ W/m^2); 4) $p = 1.75 \cdot 10^5$ Pa ($q_o(\vartheta = 0) = 3.01$ W/m^2); 5) $p = 2 \cdot 10^5$ Pa ($q_o(\vartheta = 0) = 2.38$ W/m^2). q, W/m^2; ϑ, °K.

or

$$q_0 = A\lambda \left(\frac{\beta g}{va}\right)^n \Delta T_0^{n+1}. \qquad (1a)$$

Here $\Delta T_0 = \Delta T_{0S} + \vartheta$; we will consider in a first approximation that ΔT_{0S} depends only on pressure. Then the value of ΔT_{0S} can be taken from experimental data on the boiling of a saturated liquid. Due to the smallness of these quantities for helium, they affect q_0 at small underheats only in the case $\Delta T_{0S} \ll \vartheta$ $\Delta T_0 = \vartheta$. The calculations were performed with p = (1, 1.25, 1.5, 1.75, 2)$\cdot 10^5$ Pa; ΔT_{0S} was assumed to be equal to 0.040°K, 0.029, 0.021, 0.015, 0.010°K, respectively (there is no data in the literature on ΔT_{0S} at $p > 1 \cdot 10^5$ Pa). The properties of helium were taken from [6] for a certain temperature $T = (T_S + T_\ell)/2$. It was assumed that A = 0.14 and n = 1/3 [5].

The results of the calculations are shown in Fig. 1b. It is interesting that, except for the region of very small underheats, greater pressure corresponds to a greater value of q_0 (at ϑ = const); the inverse relation $q_0 = f(p)$ exists for saturation conditions.

The experiments were conducted in a metal cryostat with two working volumes — external and internal — filled separately with liquid; the design of the unit we used is similar to that employed in [7]. The heat-emitting surface of the heater, located in the internal volume, was oriented horizontally and consisted of the end of a copper cylinder 20 mm in diameter. The heating element was wound about the opposite end of the cylinder, and germanium resistance thermometers were placed along the cylinder axis in radially drilled holes. The heater was thermally insulated with a Teflon sheath. The temperature of the liquid was measured at six points in the internal volume (and the external volume) with similar thermometers. A stabilized current source for the thermometers and an F-30 digital voltmeter were used in the temperature measurements.

The required underheating of the liquid was achieved by injecting gaseous helium from a compressed gas cylinder into the internal volume and evacuating the external volume. The wall of the internal volume was made of copper to improve heat transfer between the two volumes. The maximum underheats achieved were 2.2°K for helium and 12.5°K for hydrogen.

The temperature of the heater was determined by graphical extrapolation; the temperature of the liquid $\overline{T}_\ell$ was calculated as the arithmetic mean of the readings of the six transducers. Here, the maximum temperature was recorded directly above the heater, while the minimum temperature was recorded next to the wall of the volume. The difference between these two temperatures δT approximately characterizes the deviation of the actual temperature of the liquid

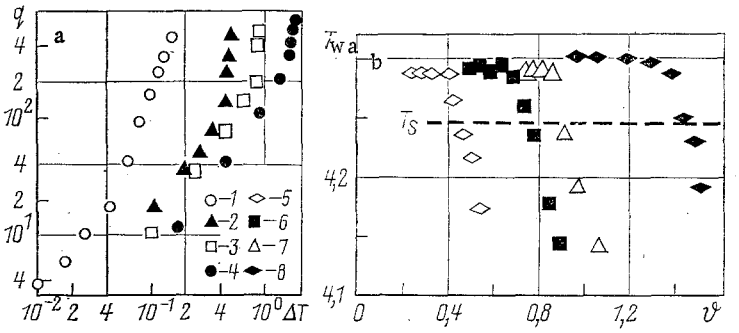

Fig. 2. Convection-boiling transition for helium at $p = 1 \cdot 10^5$ Pa: a) type A (ϑ = const): 1) $\vartheta = 0$; 2) $\vartheta = 0.341$°K; 3) $\vartheta = 0.742$°K; 4) $\vartheta = 1500$°K; b) type B (q = const): 5) $q = 7.75 \cdot 10^1$ W/m²; 6) $q = 1.32 \cdot 10^2$ W/m²; 7) $q = 1.64 \cdot 10^2$ W/m²; 8) $q = 2.57 \cdot 10^2$ W/m². q, W/m²; ϑ, ΔT and T_{st}, K.

from the mean volumetric temperature. The following equation was obtained from analysis of the data by the least squares method

$$\delta T/\overline{T}_l = Cq^{0.66}\vartheta, \tag{2}$$

where $C = 7.5 \cdot 10^{-2}$ for hydrogen; C = 1.65 for helium; q, W/m², ϑ, °K. It is important to know the temperature close to the heater at the moment of transition from convection to boiling. This temperature may be determined as $(\overline{T}_l + \delta T/2)$.

The error of the temperature measurement with the germanium thermometers is ±0.015%°K for the helium temperatures and ±0.06°K for the hydrogen temperatures.

Two types of experiments (A and B) were conducted. In the first case (A), we gradually changed the heat flux under conditions of constant underheating and pressure. Constant ϑ was achieved by changing the pressure in the external volume of the unit after each change in q. The accuracy of the maintenance of the amount of underheating using this method averaged ±0.02°K for helium and ±0.2°K for hydrogen (the standard deviation $\sigma(\vartheta)$ is shown in Tables 1 and 2) and was independent of the pressure and the absolute value of ϑ.

In the type B experiments, we changed the underheating of the liquid (again by changing the pressure in the external volume) while keep q = const and p = const.

In all of the cases, the temperature was measured after having reached a steady-state value at four to eight points for each of the regimes.

It is apparent from Fig. 2a that, when the data from the type A experiments is represented in the coordinates (q, ΔT), the regimes are distinguished from each other by the slope of the relation $q = f(\Delta T)$. Both sections are approximated by a relation of the type $q = B\Delta T^m$ using the least-squares method. Afterwards, we solved the two equations simultaneously to find the point of intersection (q_0, ΔT_0) separating the regimes at a given value of ϑ. The same method was used to analyze the data from the type B experiments, but the data here was represented in the form $T_{wa} = f(\vartheta)$ (Fig. 2b).

The value of ΔT_{0S} was determined with allowance for the correction (2) of the mean volumetric temperature for the increase in the temperature of the liquid near the heater

$$\Delta T_{0s} = \Delta T_0 - \left(\vartheta - \frac{\delta T}{2}\right) = \Delta T_0 - \left(T_s - T_l - \frac{\delta T}{2}\right). \tag{3}$$

In analyzing the above-noted errors in the measurement of T, it is easy to see that even each individual error is comparable in magnitude to the expected values of ΔT_{0S} for high pressures. The method of determining ΔT_0 introduces an additional error. In connection with this, the determination of ΔT_{0S} is quite tentative in this case. For this reason, we did not conduct type A experiments with zero and small underheats for $p \geqslant 1.5 \cdot 10^5$ Pa (helium) or $p \geqslant 4 \cdot 10^5$ Pa (hydrogen).

The position of the boundary coincided in the type A and B experiments in the case of helium. Figure 3a shows data on q_{01} ($p = 1 \cdot 10^5$ Pa) and data from [7] (we determined q_{01} here by the method described above). It is apparent that the relation $q_{01} = f(\vartheta)$ is close to

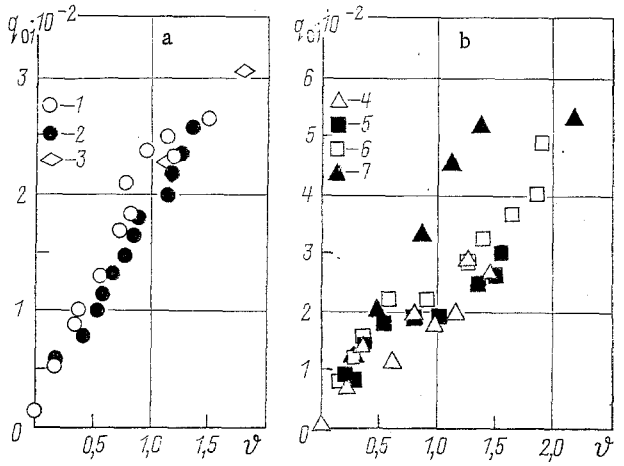

Fig. 3. Dependence $q_{o1} = f(\vartheta)$ for helium: a) $p = 1 \cdot 10^5$ Pa, 1) type A, 2) type B, 3) data from [7]; b) type A: 4) $p = 1.25 \cdot 10^5$ Pa, 5) $1.5 \cdot 10^5$ Pa, 6) $1.75 \cdot 10^5$ Pa, 7) $2 \cdot 10^5$ Pa. q_{o1}, W/m^2; ϑ, °K.

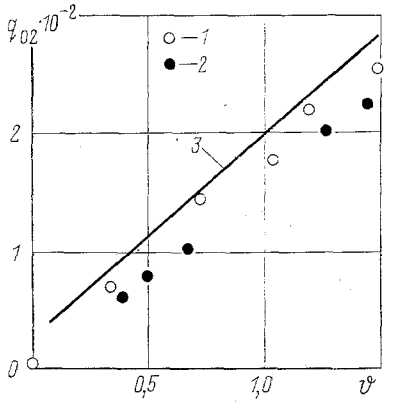

Fig. 4. Dependence $q_{o2} = f(\vartheta)$ for helium at $p = 1 \cdot 10^5$ Pa: 1) type A; 2) type B; 3) $q_{o1} = 0.27 \cdot 10^2 (1 + 6.30\vartheta)$.

linear (as in [4]); a similar result was obtained for the other pressures investigated (Fig. 3b). The data was analyzed by the least-squares method in the form

$$q_{01} = a(1 + b\vartheta) \tag{4}$$

obtained for pressures $p = (1; 1.25; 1.5; 1.75; 2) \cdot 10^5$ Pa, respectively, $a = (0.27; 0.32; 0.70; 0.66; 1.20) \cdot 10^2$ W/m^2 and $b = 6.30; 5.26; 1.97; 2.92; 1.89$ 1/K. It should be noted that Eqs. (4), can only be used at $\vartheta \geqslant 0.1$°K.

It is apparent from Fig. 3 that an increase in pressure is accompanied by a rise in the boundary to high values of q, as might be expected from the preliminary calculations. However, despite the qualitative agreement of the form of the experimental relations $q_{o1} = f(\vartheta)$ with the theoretical relations, the latter give exaggerated values of q_o. Meanwhile, the amount by which the values are exaggerated increases with an increase in ϑ. Analysis of the data on heat transfer in convection in the criteria Nu and Ra showed that an increase in underheating does not affect the exponent in (1), but the value of A tends to decrease from 0.14 at small ϑ to 0.07 at near-limiting values of same.

The data for q_{o1} for hydrogen is shown in Table 1; analysis with (4) in the investigated range of ϑ gives $a = 1.76; 0.52; 0.38; 2.06$ kW/m^2 and $b = 0.319; 0.767; 0.680; 0.057$ 1/K for the pressures $p = (1; 2; 4; 6.5) \cdot 10^5$ Pa, respectively. The effect of the direction of the transition on the position of the boundary was investigated for helium at $p = 1 \cdot 10^5$ Pa in both types of experiments. Figure 4 shows data on q_{o2} and the averaging straight line $q_{o1} = 0.27 \cdot 10^2 (1 + 6.30\vartheta)$; the experimental results confirm that q_{o2} is less than q_{o1} at equal ϑ, although the difference is not great.

The values of ΔT_{oS} are also of definite interest (despite the conditional nature of their determination); the experimental results are shown in Table 2. It turns out that in the investigated range of parameters ΔT_{oS_1} is not significantly dependent on ϑ. In connection with

TABLE 1. Effect of Pressure and Underheating on the Limiting Heat Flux q_{01} in Hydrogen Boiling (p, Pa)

$p=1\cdot10^5$ Pa										
$\bar{\vartheta}$, K	0	1,05	1,55	2,42	3,07	3,43	3,86	4,42	4,63	5,43
$\pm\sigma(\vartheta)$, K	—	0,08	0,12	0,12	0,12	0,15	0,13	0,09	0,27	0,24
q_{01}, kW/m^2	1,70	2,64	2,72	3,01	3,30	3,51	3,68	4,11	4,46	4,97
$p=2\cdot10^5$ Pa										
$\bar{\vartheta}$, K	0	0,84	1,12	1,46	1,96	2,98	5,90	7,07	7,85	
$\pm\sigma(\vartheta)$, K	—	0,16	0,31	0,17	0,22	0,15	0,24	0,41	0,22	
q_{01}, kW/m^2	0,55	0,98	1,20	1,01	1,19	1,40	3,01	3,25	3,67	
$p=4\cdot10^5$ Pa										
$\bar{\vartheta}$, K	3,19	3,66	4,16	4,69	5,56	6,63	7,60	8,66	9,66	10,56
$\pm\sigma(\vartheta)$, K	0,28	0,20	0,23	0,25	0,27	0,32	0,30	0,19	0,20	0,29
q_{01}, kW/m^2	1,14	1,26	1,69	1,78	1,87	2,18	2,07	2,60	3,21	3,07
$p=6,5\cdot10^5$ Pa										
$\bar{\vartheta}$, K	5,84	6,31	7,68	8,68	9,68	10,68	11,62	12,55		
$\pm\sigma(\vartheta)$, K	0,23	0,11	0,14	0,20	0,20	0,11	0,23	0,22		
q_{01}, kW/m^2	2,36	2,73	2,95	3,65	4,13	4,34	3,44	3,20		

TABLE 2. Effect of Pressure on the Limiting Temperature Head ΔT_{0S_1}

Helium				Hydrogen			
type A							
$p\cdot10^{-5}$, Pa	$\pm\bar{\sigma}(\vartheta)$, K	ΔT_{0S_1}, K	$\pm\sigma(\Delta T_{0S_1})$, K	$p\cdot10^{-5}$, Pa	$\pm\bar{\sigma}(\vartheta)$, K	$\Delta\bar{T}_{0S_1}$, K	$\pm\sigma(\Delta T_{0S_1})$, K
1,0	0,016	0,071	0,025	1,0	0,15	1,47	0,14
1,25	0,015	0,077	0,023	2,0	0,23	0,54	0,29
1,5	0,016	0,031	0,037	4,0	0,25	0,17	0,25
1,75	0,029	0,017	0,031	6,5	0,18	0,28	0,18
2,0	0,029	0,004	0,026				
type B							
1,0	—	0,058	0,014				

this, the table gives average values $\Delta\bar{T}_{0S_1}$ with respect to pressure, and, for comparison, the deviation from the latter $\sigma(\Delta T_{0S_1})$ and the mean error of the maintenance of ϑ = const in the type A experiments.

It is apparent from the values of $\sigma(\Delta T_{0S_1})$ shown that in some instances $\Delta T_{0S} < 0$ at high pressures, and this is precluded by physical considerations. Nevertheless, it may be seen that the mean values of ΔT_{0S_1} decrease with an increase in pressure (as with $\vartheta = 0$). Similar values of ΔT_{0S_1} were obtained in both types of experiments (helium, $p = 1\cdot10^5$ Pa). The temperature heat $\Delta T_{0S_2} \approx 0$ ($\Delta\bar{T}_{0S_2} = -0.001$°K, $\sigma(\Delta T_{0S_2}) = \pm0.012$°K type A; $\Delta\bar{T}_{0S_2} = 0.007$°K, $\sigma(\Delta T_{0S_2}) = \pm0.11$°K type B).

Comparing the mean values $\Delta\bar{T}_{0S_1}$ with the results obtained in the boiling of saturated hydrogen [8-11] (in the same pressure range), it can be seen that the agreement is not too bad with respect to both the absolute values and the form of the relation $\Delta T_{0S} = f(p)$.

As a result of the above studies, we determined the position of the boundary between the regimes of single-phase convection and nucleate boiling at $p = (1\text{-}2)\cdot10^5$ Pa, $\vartheta = 0.1\text{-}2.2$°K (helium) and $p = (1\text{-}6.5)\cdot10^5$ Pa, $\vartheta = 0\text{-}12.2$°K (hydrogen); empirical formulas were obtained to describe the position of the boundary in the coordinates (q, ϑ). The boundary is lower in the boiling-convection transition than when the transition is in the opposite direction; at the same time, the position of the boundary does not depend on which parameter changes (q or ϑ). The value of ΔT_{0S_1} does not depend on the amount of underheating and is determined only by the pressure.

It should be noted that, in analyzing the literature, we could find neither similar experimental studies of the position of the boundary between convection and boiling under

different conditions (p, ϑ) nor generally accepted, proven (similar in this sense, e.g., to S. S. Kutateladze's formula for the boundary between nucleate and film boiling) methods of calculation, even for water. Thus, the questions touched on in this article are of decided interest not only for the case of boiling of specific cryogenic liquids, but also in a broader perspective.

NOTATION

q, heat flux; p, pressure; $\vartheta = T_s - T_l$, underheating; T_s, saturation temperature; T_l, temperature of liquid; $\Delta T = T_{wa} - T_l$, $\Delta T_s = T_{wa} - T_s$; T_{wa}, temperature of heat-emitting surface; A, a, B, b, C, constants; m, n, indices; Nu, Nusselt number; Ra, Rayleigh number; λ, thermal conductivity; β, coefficient of cubical expansion; ν, kinematic viscosity; g, acceleration; σ, standard deviation. Indices: 01, conditions of convection-boiling transition; 02, conditions of boiling-convection transition.

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