CRISIS OF THE BUBBLE-TYPE BOILING OF HELIUM ON VARIOUS SURFACES

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The results of an investigation into the effects of surface coatings on the critical number q_{cr1} characterizing the bubble-type (nucleate) boiling of helium on vertical cylinders (either in free space or in a vertical channel) with natural circulation at 2.4-5°K are presented.

One of the fundamental processes of cryogenic cooling used in creating favorable conditions for superconductivity in various superconducting electrical systems is the boiling of liquid helium. The value of the critical thermal flux at which the transition takes place from bubble- to film-type boiling (the bubble-type boiling crisis, q_{cr1}) is accordingly very important in connection with such devices.

Many papers have been written in relation to the theoretical foundations of the bubble-type boiling crisis. A leading role has been played in this respect by various Soviet scientists: Kutateladze [1], Borishanskii [2], Kruzhilin [3], Labuntsov [4], and others.

A number of papers have also now been written in relation to the bubble-type boiling crisis of helium on clean surfaces in free space [5-12] and in channels with natural circulation [11-16].

It is also well known that nonmetallic coatings deposited on the heat-emitting surface have a variety of effects on the value of the first thermal-flux crisis during the boiling of liquids. Thus, Alad'ev and Yashnov showed [17] that in the case of water boiling in free space the deposition of fat (grease) on a clean heat-transferring surface reduced the value of q_{cr1}. On the other hand, experiments regarding the effect of nonmetallic coatings on the bubble-type boiling crisis of cryogenic liquids in free space carried out by Bewilogua et al. [18] in nitrogen and hydrogen, Class et al. [19] in hydrogen, Cummings and Smith [7] and Butler et al. [8] in helium show, on the other hand, that the value of q_{cr1} for surfaces with nonmetallic coatings 5-170 μm thick increases by 6-110% in comparison with the q_{cr1} for a clean surface. Only in an investigation by Lyon [5, 6] was no increase in the bubble-type boiling crisis of helium on a "contaminated" surface discovered.

Thus, at the present time there have been insufficient experiments on this theme and there is also insufficient unanimity of opinion as to the physics of boiling on coated surfaces. Further accumulation of experimental material is vital.

The aim of the present investigation was to determine the first critical thermal flux for the boiling of helium on a clean surface and on surfaces with Vaseline coatings in free space and in vertical channels with natural circulation at other than atmospheric pressure.

The experimental apparatus and the method of studying q_{cr1} for the boiling of helium in free space and in vertical annular channels under conditions of natural circulation were described earlier [11, 16].

The experiments were carried out in the helium boiling temperature range of 2.4-5°K: a) on the heated surface of a vertical stainless steel Kh18N10T cylinder d_{st} = 6 mm in diameter and 50 mm long, either clean or with a Vaseline coating, the thickness of the latter being about 40 μ; b) in annular channels 50 mm long formed between the same heated surface (clean or Vaseline-coated) and an outer polyfluoroethylene (Teflon) tube with an internal diameter of 8, 9, or 10 mm; c) in a German silver MNZhMts 30-1-1 tube with an internal diameter of 3.5 mm and 300 mm long.

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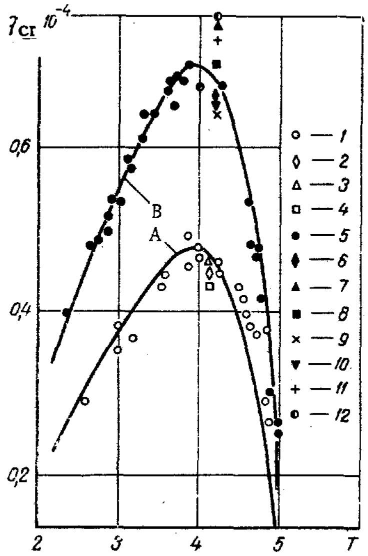

Fig. 1. Bubble-type boiling crisis of helium in free space. Clean surfaces: 1) vertical Kh18N10T steel cylinder [11]; 2) vertical copper and aluminum cylinder [10]; 3) vertical copper cylinder [9]; 4) vertical copper plate [8]. Coated surfaces: 5) authors' data; vertical copper plate [8] with various coatings: 6) 6.5-μ cellulose; 7) 18; 32; and 46-μ cellulose; 8) thin layer of Teflon + 8-μ polyamide film; 9) 12- and 25-μ polyvinyl acetate enamel; 10) four spots of cellulose 13 μ thick; 1) seven spots of cellulose 27 μ thick; 12) frozen mixture of Teflon and talc powder. A and B relate to Eq. (1). T in °K; q_{cr1} in W/m^2.

Starting from the hydrodynamic model of the boiling crisis and using the methods developed by Kutateladze and Borishanksii [1, 2], as well as Vishnev [20], we derived an equation for the bubble-type boiling crisis of a liquid on a surface inclined at various orientations,

$$(q_{cr_1})_{f.s.} = z\,(190-\varphi)^{0.5}\, r\,[g\sigma(\rho'-\rho'')(\rho'')^2]^{0.25}, \ \text{W/m}^2 \ . \qquad (1)$$

Figure 1 illustrates our data regarding the value of q_{cr1} in free space on the clean surface of a vertical cylinder and on the same surface with a Vaseline coating in the temperature range 2.4-5°K (P = 0.085-2 bars). The experimental points closely obey Eq. (1). For a clean vertical surface z = 0.0095; φ = 90 and for a Vaseline-coated vertical surface z = 0.014, φ = 90.

For comparison, the same figure illustrates Butler's results [8] for a clean vertical surface and surfaces with coatings of various kinds, and also the results of Boissin [9] and Dinaburg [10] for clean vertical cylinders, which are described by Eq. (1) (curves A and B) to an accuracy of ±10%.

We see that the value of q_{cr1} for the boiling of helium on a vertical surface (stainless steel with a Vaseline coating) is 45-50% greater than the q_{cr1} for the boiling of helium on a similar but clean vertical surface over the whole range of temperatures studied. We note that, in studying the film-type boiling crisis q_{cr2} of nitrogen and helium in free space, Pronko et al. [21] and Butler et al. [8] also noted a rise in q_{cr2} on surfaces with nonmetallic coatings as compared with clean surfaces.

A consideration of the work of Ogata et. al. [13] and Lehongre et al. [14], who studied the bubble-type boiling crisis of helium in narrow channels, shows that in developing the physical principles of the process the authors made some initial assumptions which, in our own opinion, are not very well based. In these analyses the velocity of the vapor bubbles was in fact regarded as constant along the axis of the channel, as a result of which the value of q_{cr1} depended solely on the volumetric vapor content of the flow, this being a function of the distance from the channel inlet.

Nevertheless, it was established experimentally in [22] that the velocity of the vapor increased by a factor of several times on passing along the channel.

Vishnev and Elukhin [22] established theoretically the relationship between the heat transfer associated with boiling and the reduced velocity of the vapor w_0'' in uniformly heated channels. It was also noted in [23] that the velocity of the vapor core had an intensifying action on the heat transfer associated with boiling in tubes.

The reduced velocity of the vapor which increases along the channel and has a decisive influence on boiling under conditions of natural circulation) may be expressed in the following way:

$$w_0'' = \frac{V_x''}{f}, \ \text{m/sec} \qquad (2)$$

and in turn

$$V_x'' = \frac{G_x''}{\rho''}, \ \text{m}^3 \qquad (3)$$

while

$$G_x'' = \frac{qF_x}{r}, \ \text{kg} \qquad (4)$$

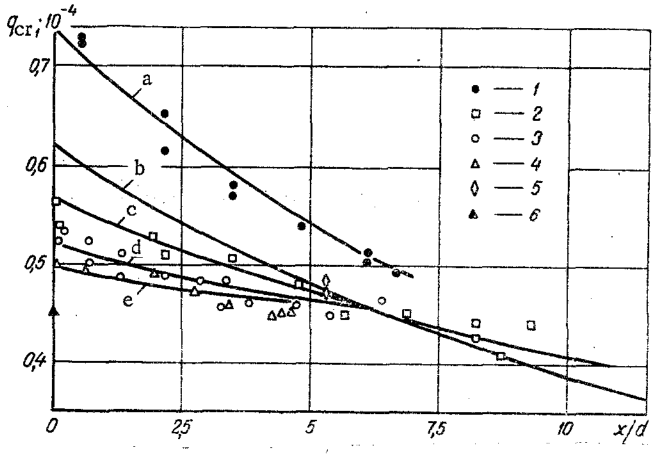

Fig. 2. Influence of the parameters x/d and l/d on the bubble-type boiling crisis of helium in vertical channels (T = 4.21°K). For an annular coated channel: 1) l/d = 6.8; clean annular channels: 2) l/d = 10.8; 3) 6.8; 4) 4.7; tube: 5) l/d = 86; free space 6) l/d = 0; a-e) corresponding calculated curves based on Eq. (10).

Thus,

$$w_0'' = \frac{qF_x}{r\rho'' f}, \text{ m/sec} \tag{5}$$

Since

$$\frac{F_x}{f} = \frac{\pi dx}{\pi \frac{d^2}{4}} = 4\frac{x}{d}, \tag{6}$$

the expression for the reduced velocity may be expressed in the form

$$(w_0'')_x = \frac{q}{r\rho''} 4 \frac{x}{d}, \text{ m/sec.} \tag{7}$$

If we assume that the reduced velocity of the vapor along the channel changes from $w_0'' = 0$ to $(w_0'')^*$ where $(w_0'')^*$ is the limiting value of the reduced velocity in the particular cross section of the channel in

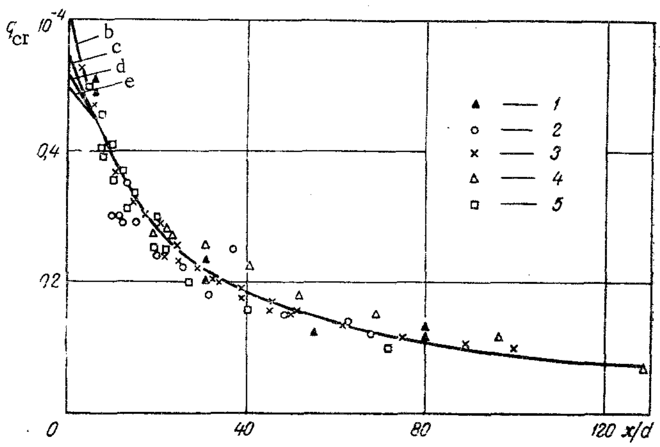

Fig. 3. Bubble-type boiling crisis of helium in vertical channels (T = 4.21°K). For a tube: 1) l/d = 86. Unilateral heating, rectangular channels: 2) l/d = 10-70 [12]; 3) 20-100 [13]. Bilateral heating rectangular channels: 4) l/d = 20-130 [12]; 5) 10-70 [15] (modified data); b)-e) calculations based on Eq. (10) for l/d = 15; 10.8; 6.8; 4.7, respectively.

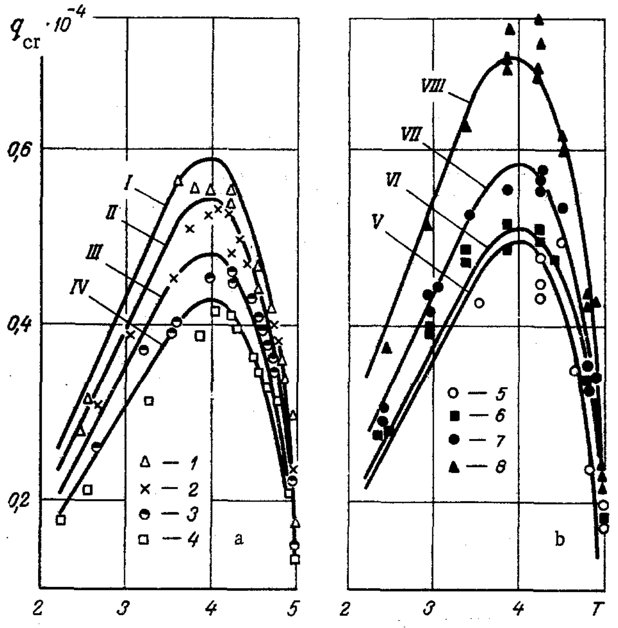

Fig. 4. Influence of the temperature of liquid helium on the bubble-type boiling crisis in vertical channels. Clean channels: a) for $l/d = 10.8$: 1) $x = 1.3$; $x/d = 0.28$; 2) $x = 9.9$; $x/d = 2.15$; 3) $x = 25$; $x/d = 5.42$; 4) $x = 43.4$; $x/d = 9.41$; b) for $l/d = 68$; 5) $x = 25$; $x/d = 3.4$; for a coated channel having $l/d = 6.8$; 6) $x = 43.5$; $x/d = 5.4$; 7) $x = 25$; $x/d = 3.4$; 8) $x = 4$; $x/d = 0.55$; I-VIII) corresponding calculations based on Eq. (11). T in °K; q_{cr1} in W/m^2.

which the whole of the liquid is evaporated, and that the bubble-type boiling crisis is inversely proportional to the increment in the reduced velocity of the vapor, the value of q_{cr1} at a distance from the channel inlet will be

$$(q_{cr1})_x = (q_{cr1})_0 \left[1 - \frac{(w_0'')_x}{(w_0'')^*}\right], \text{ W/m}^2. \tag{8}$$

Replacing $(w_0'')_x$ by its value in (7) we obtain

$$(q_{cr1})_x = \left[\frac{1}{(q_{cr1})_0} + c\,\frac{x}{d}\right]^{-1}, \text{ W/m}^2 \tag{9}$$

Clearly, the coefficient $c = 4/(w_0'')^*\rho''r$, m^2/W will be constant for a particular liquid if $p = \text{const}$.

We discovered experimentally that the first critical thermal flux for the boiling of liquid helium in a channel depended both on the reduced velocity of the vapor, expressed in terms of the rate of vaporization and the parameter x/d, and also on the ratio of the absolute dimensions of the channel in the range $0 < l/d < 15$ [16]. The equation proposed for calculating q_{cr1} in any cross section of a vertical channel during the boiling of helium under atmospheric pressure in [11, 16] is

$$(q_{cr1})_x = \left[\frac{1}{(q_{cr1})_{f.s.}} + c_1\left(c_2\,\frac{x}{d} - 0{,}04\right)\frac{l}{d}\;10^{-4}\right]^{-1}, \text{ W/m}^2 \tag{10}$$

where for clean vertical channels $c_1 = 1$ m^2/W, $c_2 = 0.0063$, for vertical channels with a Vaseline coating $c_1 = 0.3$ m^2/W, $c_2 = 0.047$; $(q_{cr1})_{f.s.}$ is obtained from Eq. (1) for clean and coated surfaces, respectively.

Equation (10) (curves a, b, c, d, e) satisfactorily describes our own experimental data for the boiling of helium in coated channels and in clean channels and tubes with $0 < l/d < 86$ (Fig. 2), and also the results of [12, 13, 15] for clean channels with $20 < l/d < 135$ (Fig. 3). This equation differs from those of Ogata et al. [13] and Lehongre et al. [14] in the range $0 < l/d < 15$, since these authors did not allow for the inhomogeneity of the flow and the slipping of the individual phases in the latter, which is especially appreciable in channels with small l/d. For $l/d > 15$ the influence of the absolute ratio l/d remains constant in view of the fact that the increase in the rate of liquid circulation has ceased. In this case we put $l/d = 15$ in Eq. (10) and the results closely approach those of [13, 14].

The effect of temperature (pressure) on the bubble-type boiling crisis is taken into account in Eq. (1). In view of this it is convenient to unify Eqs. (1) and (10) in order to describe the boiling crisis in channels at various pressures. To this end, instead of $(q_{cr1})_{f.s.}$ in Eq. (10), we introduce its value taken from Eq. (1); as a result of this we obtain the following equation for the boiling of helium in vertical channels:

$$(q_{cr_1})_x = \frac{(q_{cr_1})_{f.s.}}{1 + (q_{cr_1})_{f.s.} c_1 \left[\left(\frac{\rho_e''}{\rho''} \right)^{0.5} \frac{r_e}{r} c_2 \frac{x}{d} - 0.04 \right] \frac{l}{d} \cdot 10^{-4}}, \text{ W/m}^2. \quad (11)$$

For all liquids ρ_e'' and r_e correspond to the density and heat of vaporization at $P \simeq 0.35\ P_{cr}$. For helium ρ_e'' and r_e correspond to the values at $0.35 P_{cr} \simeq 1$ bar ($T_e \simeq 0.8\ T_{cr} = 4.1$ K); then q_{cr1} takes its maximum value [20].

Figure 4 shows our own experimental data regarding the first critical thermal flux for clean vertical channels with $l/d = 10.8$ in four cross sections having x/d equal to 0.28; 2.15; 5.42; 9.41 [11] and $l/d = 6.8$ in the cross section x/d = 3.4, and also for a vertical channel with a Vaseline coating having $l/d = 6.8$ in three cross sections, x/d = 0.55, 3.4, and 5.9, at temperatures of 2.4-5°K. The continuous lines correspond to calculations based on Eq. (11) (curves I-VIII). We see that the calculated curves and experimental data are in excellent agreement, the maximum discrepancy not exceeding ±10%.

Figures 2 and 4 show that for identical geometrical parameters of the channels the value of q_{cr1} in a coated channel is greater than the value of q_{cr1} for the boiling of helium in a clean channel (curves a and d in Fig. 2 and VII and V in Fig. 4). It should also be noted (see Fig. 2) that the difference in the values of q_{cr1} for the clean and coated channels is 40-50% at the inlet and 15-25% at the outlet.

Equation (11) is capable of describing the process for various pressures in vertical channels with natural circulation contours similar to the experimental geometry, and also (on putting $l/d = 0$) in a large volume. Thus, Eq. (11) links the bubble-boiling crisis in free space and in channels.

Equation (11) corresponds to the general hydrodynamic theory of the bubble-type boiling crisis developed by Kutateladze and Borishanskii [1, 2], and it excellently supports our proposed mechanism for the development of the boiling crisis under conditions of natural liquid circulation [16].

As experimental data regarding the bubble-type boiling crisis accumulate for surfaces with different types of coating, the quantities c_1 and c_2 in Eqs. (10) and (11) may be refined further. Equation (11) is suitable for engineers' calculations regarding the boiling process in channels with unilateral and bilateral heating, and also in free space on clean surfaces and surfaces coated with nonmetallic materials under conditions similar to those ruling in the experiments.

NOTATION

x	is the distance from the channel inlet;
l	is the absolute length of the channel;
d	is the thermal equivalent diameter;
q	is the thermal flux;
q_{cr1}	is the first critical thermal flux;
$(q_{cr1})_{f.s.}$; $(q_{cr1})_0$; $(q_{cr1})_x$	are the first critical thermal flux in free space, at zero distance from the channel inlet, and at a distance x from the channel inlet, respectively;
ρ', ρ''	are the densities of the liquid and vapor;
r	is the heat of vaporization;
T	is the boiling point of the liquid in the pool (bath);
ρ_e'', r_e, T_e	are the extremal vapor density, heat of vaporization, and temperature;
P	is the pressure;
P_{cr}, T_{cr}	are the critical pressure and temperature;
σ	is the surface tension;
g	is the gravitational acceleration;
φ	is the relative inclination of the surface to the horizontal;
w_0''	is the reduced velocity of the vapor;

z is the hydrodynamic stability coefficient of the process;
V''_x, is the volume of vapor passing through the cross section at a distance x;
G_x'' is the amount of vapor on the surface of the channel prior to the cross section at a distance x;
F_x is the heat-transfer surface of the channel under consideration;
f is the cross-sectional area of the channel.

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