A STUDY OF CRITICAL FILM BOILING UNDER NATURAL CONVECTION

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UDC 536.423.1;536.252

Results are shown of a study concerning the critical film boiling of various cryogenic liquids. The physical mechanism of this process is analyzed and recommendations are made for calculating it.

In several studies concerned with the second critical boiling mode it has been shown by experiment that the critical temperature T_{cr2} depends on the properties of the wall material and is in many cases higher than the critical temperature of the boiling liquid T_{cr} [1-3]. This evidence can be explained neither by the thermal resistance of the wall nor from the standpoint of hydrodynamic and thermodynamic mechanisms of the critical boiling mode.

In this study the authors have developed a physical model of the phenomenon and test results are presented here relating to the critical film boiling of cryogenic liquids under nonsteady cooling conditions. *

The necessary conditions for critical film boiling are that the interphase boundary becomes hydrodynamically unstable [4] while the liquid remain thermodynamically stable upon contact with the wall [5]. The character of the critical mode depends on which of these two factors is the governing one.

If the interphase boundary becomes unstable at a sufficiently high wall temperature, then there will occur intermittent contacts between liquid and wall. At the contact boundary the temperature will then reach some level T_{cb} which, to the first approximation, can be found by solving the problem of transient heat conduction for semiinfinite layers of liquid and a semiinfinite wall with initial temperatures T_{Lo} and T_{wo} respectively [6]:

$$T_{cb} = T_{Lo} + \frac{T_{wo} - T_{Lo}}{1 + \sqrt{\frac{(\rho c\lambda)_L}{(\rho c\lambda)_w}}}. \tag{1}$$

If the local temperature at the contact boundary between liquid and wall exceeds the limit of metastable superheat T_{ls}, then momentary effervescence will occur. † If $T_{cb} \leq T_{ls}$, however, then the time of contact between liquid and wall will be longer and the thermal flux will increase as a result of transient heat conduction into the liquid and as a result of bubble boiling — the flux having sufficient time now to develop. When bubble boiling occurs, T_{cb} becomes lower than estimated according to Eq. (1). Consequently, critical film boiling is possible at $T_{cb} \leq T_{ls}$ even if the mean wall temperature $T_{wo} = T_{cr} > T_{ls}$.

The preceding analysis suggests that the temperature of critical boiling T_{cr2} may depend on the thermophysical properties of the liquid and of the wall, on the state variables of the liquid, and on the conditions of its contact with the wall (wettability, surface roughness, geometry). The aim of our experimental study was to establish the relation between T_{cr2} and all these factors.

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*Results obtained in the first part of this study were presented in [8].

†In the case of cryogenic liquids, a contact lasts for 10^{-3}-10^{-6} sec and the effervescing layer is 10^{-5}-10^{-6} cm thick.

Institute of Aviation, Moscow. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 24, No. 2, pp. 205-210, February, 1973. Original article submitted May 22, 1972.

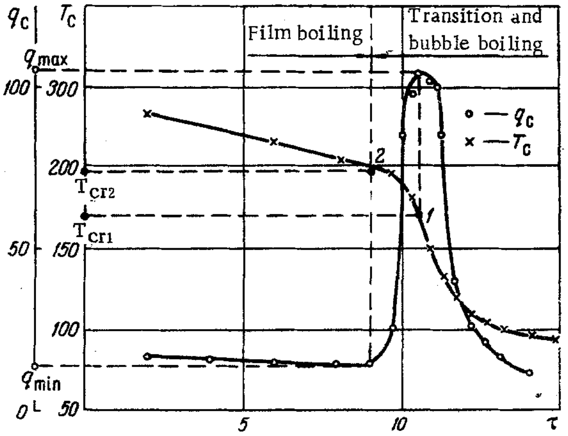

Fig. 1. Typical variation of the wall temperature T(°K) and of the thermal flux q (kW/m²) with time τ (sec).

The tests were performed in thermally insulated containers under atmospheric pressure. The test liquids were nitrogen, oxygen, Freon-12, Freon-13, and Freon-22. The active container segments were vertical tubular or annular channels made of various materials (stainless steel, copper, duralumin, magnesium and titanium alloys, and Teflon-coated steel), of various shapes, and of various degrees of surface roughness. On the thermally insulated (outside) surface of the tube wall were stuck copper-constantan thermocouples with size 0.1 mm (diameter) wires.

A test container initially at the temperature of stable film boiling was immersed into the liquid. While it was cooling down, the temperature of the tube wall at 8-12 sections and the temperature of the liquid were measured and recorded, as functions of time, with a model OT-24 oscillograph.

Typical curves of temperature and thermal flux variations with time during cooling are shown in Fig. 1.

Critical film boiling was assumed to start at the time τ_{cr2} corresponding to the minimum value of derivative $dT_0/d\tau$. The temperature drop across the tube wall was accounted for according to the solution to the reverse problem of heat conduction [7]:

$$T_{cr2} = T_0(\tau_{cr2}) + \frac{\delta_w^2}{2a_w}\left(1 \pm \frac{2}{3}\frac{\delta_w}{D_v}\right)\frac{dT_0}{d\tau} \tag{2}$$

(the plus sign referring to boiling on the outside tube surface and the minus sign referring to boiling on the inside tube surface).

For the case of boiling on the outside of a tube with a wall thickness δ_w and coated with a layer of thickness δ_{coat}, we have derived the following formula

$$T_{cr2} = T_0 + \left[\frac{\delta_w^2}{a_w}\left(1 + \frac{2}{3}\frac{\delta_w}{D_0}\right) + \frac{\delta_{coat}^2}{2a_{coat}} + \frac{(\rho c\delta)_w\delta_{coat}}{\lambda_{coat}}\left(1 - \frac{\delta_c}{D_{c_1}}\right)\right]\frac{dT_0}{d\tau}, \tag{3}$$

where D_{c1} denotes the diameter to the boundary between base material and coating.

Each series of test data obtained under the same conditions was evaluated statistically. The error in determining τ_{cr} due to leakage along the wall was estimated according to the formula

$$\Delta \leqslant \frac{a_w}{u_{cr}^2}\left(\frac{dT_0}{d\tau}\right)_{max}, \tag{4}$$

with u_{cr} denoting the rate of the critical boiling mode along the tube and calculated by a graphical differentiation of function $\tau_{cr2} = f(z)$.

Including the accuracy of measurement and data evaluation, the nominal error in calculating the temperature difference $(T_{cr2} - T_0)$ did not exceed ±20%.

Preliminary tests have shown that the temperature of critical boiling does not depend on the depth of tube immersion in the liquid nor on the axial coordinate of a section. The effect of surface roughness was examined on the same active container segment of grade 1Kh18N9T steel tubing with an initial surface finish ∇6, first polished to ∇14 and then roughed to ∇1. No relation between the T_{cr2} point and the surface roughness was detected during boiling of liquid nitrogen. This could be explained by the fact that the surface asperities were smaller than the mean thickness of the vapor film. In the case of cryogenic liquids

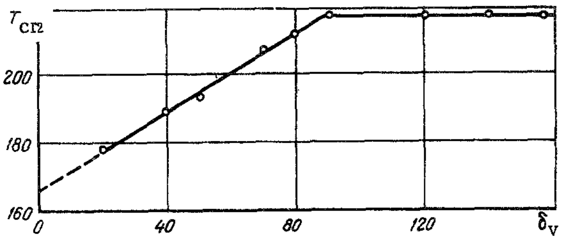

Fig. 2. Temperature of critical film boiling of liquid nitrogen, as a function of the thickness of grade FP-3 Teflon coating on a stainless steel tube δ (μm).

with a wetting angle θ close to 0° in contact with the wall, the valleys were completely filled with liquid and were thus eliminated as additional vapor nucleation centers.

The effect of geometrical factors on critical film boiling was examined on liquid nitrogen in tubes 4, 6, 10, 20, and 40 mm in diameter as well as in annular gaps 1.7, 2.7, and 4.7 mm wide (D_e 3.4, 5.4, and 9.4 mm respectively), also in a large pool around a tube with an outside diameter $D = 1.6$ mm. In the last case and in gaps of an equivalent diameter $D_e > 6$ mm, critical boiling occurred at the same T_{cr2} point. In gaps with $D_e < 6$ mm, the T_{cr2} point dropped as the diameter was decreased. This could be explained by a higher frequency of contacts between liquid and wall at a gap size approaching the capillary constant for a given liquid substance $\sqrt{\sigma/g(\rho_L-\rho_V)}$, which determines the geometrical parameters of surface waves.

The effect of subheat on the temperature of critical boiling for a given liquid was examined while steel surfaces were cooled in liquid nitrogen, Freon-12, and Freon-22. We have found that the effect of subheat may become weaker with a decrease in the parameter $(\rho c\lambda)_W$, inasmuch as the effect of thermal flux (due to already developed bubble boiling) on lowering the T_{cr2} point becomes stronger. The effect of the thermophysical properties of the wall material was examined with liquid nitrogen and Freon-13 boiling in container segments of various materials. It has been found that the T_{cr2} point rises with increasing subheat of the liquid and with a decreasing thermal activity coefficient $\sqrt{(\rho c\lambda)_W}$ of the wall. As the subheat increases (i. e., as the temperature of the liquid drops), the same T_{cb} temperature at the contact boundary between liquid and wall will be established at a higher mean wall temperature T_{wo}. A wall material with a lower value of $\sqrt{(\rho c\lambda)_W}$ will reach the same T_{cb} temperature at a higher T_{wo} temperature than a wall material with a higher value of $\sqrt{(\rho c\lambda)_W}$.

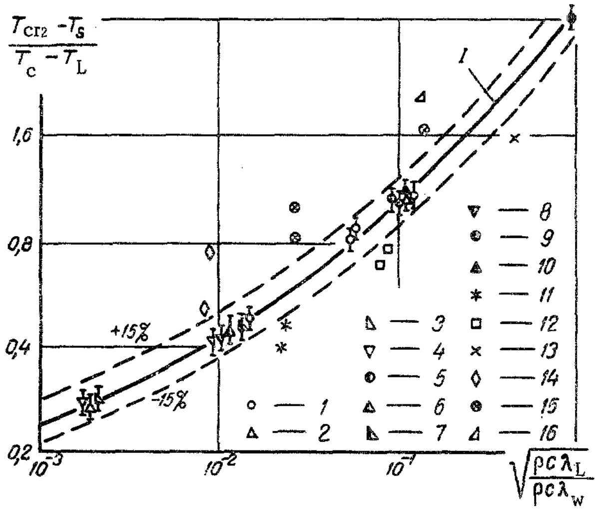

Fig. 3. Generalization of test data pertaining to the temperature of critical film boiling: copper and nitrogen (1), Freon-13 (2), Freon-22 (3), Freon-12 (4), steel tube and nitrogen (5), Freon-13 (6), Freon-22 (7), Freon-12 (8), grade FP-3 coating and nitrogen (9), Freon-13 (10), aluminum and water (11), steel and water (12), glass and water (13), aluminum and ethanol (14), steel and ethanol (15), glass and ethanol (16), calculations according to Eq. (1) (I). Each point on the graph represents the average value from all tests with a given value of the ratio $(\rho c\lambda)_L/(\rho c\lambda)_W$.

The relation between the T_{cr2} point and the thickness δ_{coat} of a low-(thermal) conductivity grade FP-3 coating on a stainless steel tube was examined in a special experiment. The test results shown in Fig. 2 indicate that the T_{cr2} point ceases to depend on δ_{coat} when $\delta_{coat} \geq 90\ \mu m$. An explanation for this can be found in the Fourier number for the coating $Fo_{coat} = a_{coat}\tau_c/\delta^2_{coat} \leq 0.25$ with $\delta_{coat} \geq 90 \mu m$ and actual contact times τ_c between liquid and wall under such conditions. In this case the thermal signal does not have sufficient time to reach the metallic base and the coating behaves as if it were infinitely thick.

When $\delta_{coat} < 90\ \mu m$, then $Fo > 0.25$ and, because of the heat coming from the metallic base, the contact is interrupted within a time shorter than τ_c. The heat transfer abates and, consequently, the T_{cr2} point drops. The condition that $Fo = 0.25$ for $\delta_{coat} = 90\ \mu m$ has yielded an approximate length of $\tau_c = 0.01$ sec. The test values for the T_{cr2} point of five cryogenic liquids and six wall materials (including coatings with $Fo_{coat} < 0.25$) have been generalized by the equation

$$\frac{T_{cr2}-T_o}{T_k-T_n} = 1.65 + 2.5\left[\frac{(\rho c\lambda)_L}{(\rho c\lambda)_w}\right]^{0.25} + \frac{(\rho c\lambda)_L}{(\rho c\lambda)_w}. \tag{5}$$

This is shown in Fig. 3.

Formula (5) is applicable to the following range of parameter values:

$$\sqrt{\frac{(\rho c\lambda)_L}{(\rho c\lambda)_w}} = 10^{-3} - 1{,}0; \quad \frac{P}{P_k} = 0.02 - 0.03;$$

$$\theta = 0; \quad D_e\sqrt{\frac{g(\rho_L - \rho_V)}{\sigma}} \geqslant 6;$$

$$\frac{c_L(T_n - T_L)}{r} = 0 - 0.2.$$

In Fig. 3 are also shown test data from [3], obtained in a study of critical film boiling in the spherical state. A very interesting fact has been established in these experiments over this entire range of parameter values, namely that the ratio of $T_{cr2}-T_0$ to the temperature difference corresponding to the maximum thermal flux point on the boiling curve $q_w = f(T_w-T_0)$ is constant and that $(T_{cr2}-T)/(T_{cr1}-T_0) = 1.6$ within a ±20% accuracy. The T_{cr1} point is usually regarded as the temperature of critical bubble boiling. With Eq. (5), it now becomes possible to calculate T_{cr1} as well. The T_{cr1} point is found from tests, as the point on the $T_w = f(\tau)$ curve where $\partial T_w/\partial\tau$ and q_w are both minimum (Fig. 1).

NOTATION

T	is the temperature, °K;
ρ	is the density;
c	is the specific heat;
λ	is thermal conductivity;
a	is the thermal diffusivity;
δ	is the wall thickness;
τ	is the time;
z	is the axial coordinate;
σ	is the coefficient of surface tension;
r	is the latent heat of evaporation.

Subscripts

w	refers to wall;
cb	refers to contact boundary between liquid and wall;
L	refers to liquid;
V	refers to vapor;
cr	refers to critical mode;
o	refers to outside surface;
coat	refers to coating;
e	refers to equivalent dimension;
ls	refers to limit of metastable superheat;
n	refers to beginning of time count.

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