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EXPERIMENTAL INVESTIGATION OF THE THERMODYNAMIC CRISIS OF FILM BOILING

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UDC 536.423.1

It is shown on the basis of experimental data that the thermodynamic crisis of film boiling depends on the material at the surface of the cooled solid. A theory substantiating the effect of the thermophysical characteristics of the surface on the crisis temperature in steady-state film boiling is proposed.

Reduction of the cooling time for metal structures washed by low-boiling liquids constitutes a pressing problem involving many cryogenic systems and devices. In cooling objects to operating temperatures under conditions where the vapor temperature near the vapor film—dispersoid boundary is close to the saturation temperature, the total cooling time can be reduced by diminishing the relative share of the wall's heat resource taken off during film boiling, i.e., by switching to intermediate, more intensive types of boiling at a temperature higher than $T = T_{lp}$.

Many investigators have noted on the basis of experimental results that the film boiling crisis, the transition to nucleate boiling, depends on the material at the surface of the cooled solid [1-5]. In particular, it has been found that coating of the solid to be cooled with a thin film of a material possessing a low thermal-conductivity coefficient sometimes leads to a higher temperature of thermodynamic crisis of film boiling. With the exception of [1], the many attempts at explaining this phenomenon were unsuccessful. In our opinion, this is due to a lack of a sufficient amount of experimental data and the contradictory nature of the data on the relative effect on the film boiling crisis of coating the parts to be cooled with various materials. It has been proved [3] that a stationary model cannot be used to explain the effect of coatings (or the effect of the material at the surface). On the other hand, in many cases an increase in the coating thickness (beyond certain values) had a similar effect on the cooling rate of a solid, as in the case of the stationary model. This necessitated new theoretical and experimental investigations.

Figures 1 and 2 show the effect of various coatings and of their thickness on the cooling time of specimens in liquid nitrogen. The cooling is accelerated as a result of passage to efficient types of boiling (in comparison with stable film boiling) at higher mean temperatures of the specimen.

The experimental values of the mean-mass temperature of a solid cooled in liquid nitrogen corresponding to the crisis of stable film boiling are obtained by processing the cooling curves $T(\tau)$ for the experimental specimens, the dimensions of which are determined (on the basis of theoretical estimates, using the similarity theory and regular conditions) with an allowance for the virtual absence of a temperature gradient along the wall thickness; i.e., $Bi \ll 1$ and $T_W \cong T_{W_0}$. The temperature of the experimental specimen at the time of sharp change in the slope of the cooling curve is used as the temperature boundary of the thermodynamic crisis of film boiling (Fig. 3).

The absence of a clearly defined temperature boundary of change under the heat-transfer conditions is a characteristic of the film boiling crisis. This cannot be explained only by the adopted method of experimental data processing; it is connected with the complex effect

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Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 34, No. 5, pp. 785-791, May, 1978. Original article submitted May 19, 1977.

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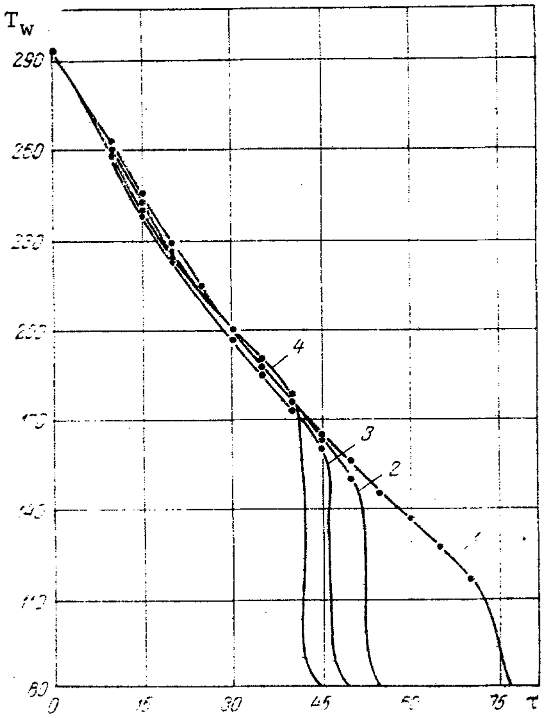

Fig. 1. Cooling curves for a horizontal St Kh18N9T ⌀56 × 2 cylinder with an FP-734 coating. 1) $\delta = 0$; 2) $\delta = 80$ μm; 3) 120 μm; 4) 240 μm; T_w, °K; τ, sec.

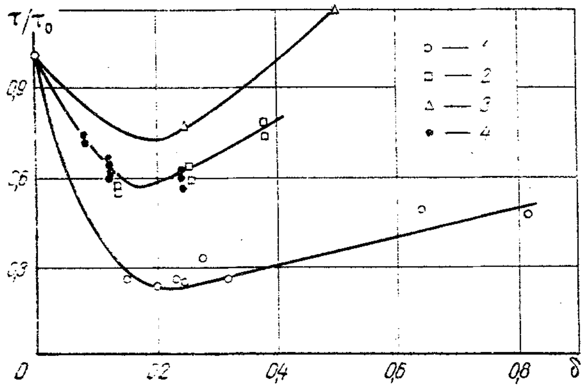

Fig. 2. Comparison of the experimental data with data from [6] on the reduction of the cooling time of specimens with the following coatings: 1) Vaseline; 2) Teflon; 3) asbestos; 4) FP-734.

of the thermophysical characteristics of the material and with the hydrodynamic conditions of the cooled surface. In order to determine the surface temperature corresponding to the film boiling crisis, it is necessary to repeat the experiments many times and use the statistical method of data processing. The values obtained both experimentally and theoretically, corresponding to the maxima of the distribution curves for the stochastic boundary of the film boiling crisis, are given in Table 1.

The strongly pronounced effect of the thermophysical characteristics of the surface material is noteworthy.

An attempt was made in [7] to explain the dependence of the temperature boundary of the second boiling crisis on the thermophysical characteristics of the cooled surface by the thermal contact between the surface and the liquid. The authors indicate [7] that the contact time in this case must be equal to 0.01-0.008 sec.

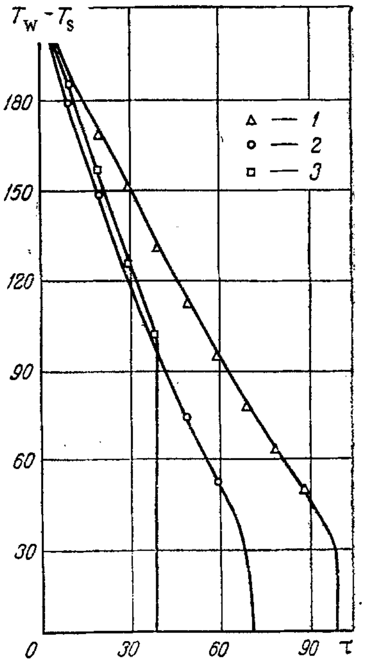

Fig. 3. Mean-mass temperature curves in the cooling of vertical cylindrical specimens. 1) ⌀ 30 × 3, 5-Si; 2) ⌀ 30 × 2, St Kh18N9T; 3) ⌀ 30 × 2, St Kh18N9T with FP-734; δ = 240 μm.

The experimental data on T_{cr} for cryogenic liquids under conditions of free or forced convection are generalized with a scatter of ±30% by means of the following equation in [7]:

$$\frac{T_{cr} - T_s}{T^* - T_l} = 0.165 + 2.5\left[\frac{(\rho c\lambda)_l}{(\rho c\lambda)_w}\right]^{0.25} + \frac{(\rho c\lambda)_l}{(\rho c\lambda)_w}. \qquad (1)$$

In spite of the fact that our earlier experimental data are in satisfactory agreement with both the experimental data and the above dependence (1), we considered it advisable to process the experimental data and explain the causes of the thermodynamic crisis of film boiling on the basis of a two-stage heat-transfer model accounting for the nonwettability of the wall by the liquid, i.e., accounting for the fact that heat is transmitted from the wall to the liquid through a vapor film which steadily blocks the wall surface.

The analysis is based on the following assumptions.

The thermal resistance to heat transfer from vapor to the liquid can be neglected because it is small in comparison with the thermal resistance to heat transfer from the wall to vapor; i.e., $\alpha_w F_w/\alpha_i F_i \ll 1$. The vapor temperature in the flow core is equal to $T_v = T_s$. The vapor velocity and temperature are constant along the core thickness; the vapor discharge through the laminar sublayer can be neglected.

It is important to note that these assumptions presuppose that the vapor temperature at the boundary of the laminar sublayer is equal to the saturation temperature, so that the temperature head of heat transfer from vapor to the liquid can be neglected.

In our opinion, the confirmation of this is to be found in the nonuniformity of the layer — the saturation of the turbulent part of the flow with minute liquid droplets. The existence of such a gas—liquid dispersoid should strongly affect the temperature distribution pattern in the layer. The presence of a highly developed phase interface in the layer results in the fact that vaporization actually occurs here in the volume rather than at the boundary of the liquid core. The vaporization sources cause a sharp increase in the effective specific heat. Moreover, if we consider that the presence of a heavy suspension (liquid drops) in the vapor causes the effective thermal conductivity to increase, we can assume that the entire temperature drop ($T_w - T_s$) pertains to the laminar vapor film — the molecular thermal-conductivity layer. These assumptions are in good agreement with experimental data [8], which indicate that the thin boundary layer of vapor is responsible for most of the thermal

TABLE 1. Film Boiling Temperatures for Certain Materials

Material at the cooled surface	Temp. of film boiling crisis, °K	Material of cooled surface	Temp. of film boiling crisis, °K
Copper	110	Ice (water)	130
Lead	113	Wax	146
Kovar	111	Graphitic Teflon	172
German silver	114	FP-734 fluoroplastic	180
Stainless steel	115		

resistance, while the temperature gradient is close to zero in the remaining part of the vapor film.

The heat-transfer process is complicated substantially by the fact that the vapor film actually experiences oscillatory action under film boiling conditions, while the interface between the vapor—liquid dispersoid and the liquid has a periodically varying wave form rather than a smooth, fixed shape. The mean oscillation frequency of the vapor film at the surfaces of horizontal and vertical cylinders with d = 60 mm and l = 200 mm is equal to 25-50 Hz for benzene and normal hexane according to data from [9]. The rising motion of the vapor and the oscillations of the dispersoid surface lead to oscillatory wave motions of the interface between the laminar sublayer and the dispersoid. In any of the cross sections in question, the thickness of the boundary laminar sublayer changes periodically in time at a frequency equal to the oscillation frequency of the vapor—liquid dispersoid. The wave character of the vapor flow in the laminar sublayer produces two important results: 1) The surface area of the interface at the boundary of the laminar sublayer increases considerably; 2) depending on the laminar film thickness, the coefficient of heat transfer varies periodically in any section. As was mentioned in many papers [10, 11], a sharp increase in the heat-transfer coefficient is possible as a result of vortices in wave troughs. The increase in the surface area is reflected in the thermal flux increase in comparison with the theoretical value for a smooth interface.

Although it should not substantially influence the mean value of heat transfer (because of the small surface area and the short contact time), the sharp increase in the local heat-transfer coefficient over the cross section at the time of wave passage leads to a response reaction of the surface of the solid — fluctuation of the surface temperature.

If we assume that the amplitude of these oscillations reaches a considerable value in certain cases, the effect exercised by the thermophysical characteristics of the surface material could be explained in the most general way as follows (Fig. 4). Since the maximum of the local surface temperatures is equal to the temperature of the solid at a sufficiently large distance from the surface, where temperature disturbances are virtually absent, the upper envelope constitutes the curve of the mean-mass temperature of the solid. So long as the temperature of the layers adjacent to the surface is sufficiently high, the minimum local temperature values at the surface of the solid stay above the limiting overheat temperature T_{lp}, which ensures stable film boiling. As soon as the temperature of the layers adjacent to the cooled surface drops to $T < T_{lp}$, conditions are created for surface wetting by the liquid, the vapor film loses its stability over individual surface sections, and the film boiling conditions are replaced by transitional forms and finally by nucleate boiling. Thus, the thermodynamic crisis temperature of film boiling is related to the temperature fluctuations at the surface of the solid by the following simple expression:

$$T_{\mathrm{cr}} = T_{l\mathrm{p}} + \Delta T_{\mathrm{w}_0}. \tag{2}$$

If we consider the formal analogy between the temperature fluctuations of the cooled surface under film boiling conditions and in the case of steady-state periodic variation of the ambient temperature, we can use the rigorous mathematical solution for an approximate estimate.

As is known, the amplitude of surface temperature oscillations in general form for the case of stationary-periodic variations of the ambient temperature is expressed as follows:

$$A_0 \equiv \frac{\Delta T_{\mathrm{w}_0}}{\Delta T_{l\mathrm{p}}} = f\left(\mathrm{Bi}^* = \frac{\alpha}{\sqrt{\lambda c \rho \omega}}\right). \tag{3}$$

Assuming (momentarily, for the purpose of a rather rough estimate) that the values of α and ω are invariant and that they are independent of the thermophysical characteristics of

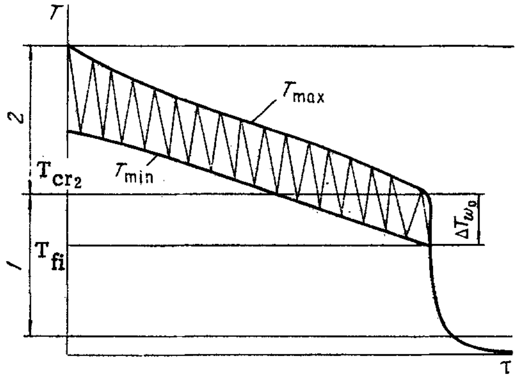

Fig. 4. Local temperature variation at the surface of the cooled solid: 1) zone of transitional and nucleate boiling; 2) zone of stable film boiling.

the surface, we obtain the following approximate expression for the ratio of the amplitude of surface temperature fluctuations for two different materials:

$$\frac{\Delta T_1}{\Delta T_2} \simeq \sqrt{\frac{(\lambda c\rho)_2}{(\lambda c\rho)_1}}. \tag{4}$$

The ratio of the above data, obtained experimentally and by calculation, for Teflon and stainless steel surfaces has the following value:

$$\frac{T_{\mathrm{Te}} - T_{l_\mathrm{p}}}{T_{\mathrm{sst}} - T_{l_\mathrm{p}}} = \frac{180 - 107}{115 - 107} = 9.1.$$

According to (4) this ratio equals

$$\frac{T_{\mathrm{Te}} - T_{l_\mathrm{p}}}{T_{\mathrm{sst}} - T_{l_\mathrm{p}}} = \sqrt{\frac{(\lambda c\rho)_{\mathrm{sst}}}{(\lambda c\rho)_{\mathrm{Te}}}} = \sqrt{\frac{9.5\cdot 0.068\cdot 7900}{0.22\cdot 0.15\cdot 1400}} = 10.5.$$

We can say that, with an allowance for the assumptions made, the obtained values are in good agreement with each other. Such an approximate correspondence is observed for all the investigated materials at the cooled surface under film boiling conditions. Thus, it can be said that the thermophysical characteristics of the surface exert a considerable effect on the temperature boundary of the second boiling crisis.

However, Eq. (4) can be considered only as an approximate estimate of the effect exerted by the thermophysical characteristics of the surface, since the problem of the limits of variation in the heat-transfer coefficient and the frequency of surface temperature fluctuations with regard to different parameters of film boiling conditions require further elucidation.

NOTATION

T, temperature; τ, time; ρ, density; λ, coefficient of thermal conductivity; c, specific heat; α, heat-transfer coefficient; F, surface area; d, diameter; l, length; ω, angular frequency of oscillations. Indices: lp, limiting process; w, wall; w_0, wall surface; l, liquid; cr, film boiling crisis; s, state of saturation; i, phase interface.

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HEAT TRANSFER FOR A LIQUID BOILING IN A BED OF GRANULAR MATERIAL

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UDC 536.423.1:541.182

An approximate analytical model is given for heat transfer during boiling in a bed of granular material, and this is used in a generalization from the published data.

Boiling in granular beds is a promising technique for the design of heat-transfer systems [1, 2] and other types of process plant [3-6]. This requires a better understanding of the physical processes in such beds. There were marked differences between the conditions of [1, 2] and of [3, 4, 7], as Fig. 1 shows, since $H/b \ll 1$ in [1, 2] for $\rho_g/\rho' \gg 1$, whereas $H/b \gg 1$ for $\rho_g/\rho' = 1.5\text{-}3$ in [3, 4, 7]. Therefore, one assumes that there was gravitational pressure of the particles on the wall in [1, 2]. On the other hand, in [3, 4, 7] the particles near the wall were largely relieved from the pressure of the overlying layers, $H/b \gg 1$, and so they were probably displaced from the wall. In [7], this displacement was detected photographically. If one assumes that the main heat-transport mechanism is determined by the processes at the wall for boiling in a bed, then there should be an analogy with a process in a horizontal slot having an equivalent width which is proportional to the particle size. Comparison of [3, 4, 7] with [10, 11] confirms that the behavior of the heat-transfer coefficients is much the same in both cases. On the other hand, boiling in a bed differs from that in a horizontal slot in that the gas—liquid mixture migrates in much the same way as in fluidization. The smaller the particles and the shallower the bed, or the higher the thermal loading, the greater the influence of fluidization. The particles can be completely suspended by a thermal fluidization mechanism, and then the main heat-transfer mechanism would be as for a free volume of liquid. The particles have an effect via the effective thermophysical characteristics of the liquid—particle medium (viscosity μ_e, thermal conductivity λ_e, specific heat c_e, etc.). Therefore, standard equations for heat transfer in boiling can be used with the effective constants and the semiempirical relationships for horizontal slots [10, 11] to construct an approximate model for boiling in a displaced granular bed. It is then very important to define a criterion that determines the contribution from any particular mechanism. This is possible if we compare the characteristic boiling rate $u = q/r\rho''$ with a characteristic of the fluidization, namely, the critical fluidization speed $u_{cr} = C_{cr} g d^2 \cdot (\rho_g - \rho')/\mu'$ [12], where C_{cr} is a numerical constant dependent on the mode of flow around a suspended particle. Therefore, we have for the total heat flux in this granular bed that

$$q = q_1(1-\psi) + q_0\psi, \tag{1}$$

where q_1 is the heat flux transported in the process analogous to boiling in a horizontal slot and q_0 is the heat flux transported by the nominal process analogous to that in a free volume of liquid with the effective thermophysical parameters, while ψ is an interpolation factor, which is the ratio u/u_{cr}, which can be put in the following form on passing to the limit:

$$\psi = \frac{u}{u_{cr} + u}. \tag{2}$$

Further, q_0 is dependent on the working conditions, the physical and geometrical parameters, and so on [13-15, et al.]. A semiempirical relationship for q_1 has been derived from the experimental data of [10, 11] by means of a physical model for boiling in a horizontal slot. The basic features of this model are as follows.

Odessa Refrigeration-Technology Institute. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 34, No. 5, pp. 792-798, May, 1978. Original article submitted January 13, 1977.

0022-0841/78/3405-0539$07.50