CORRELATION OF FILM-BOILING THERMODYNAMIC CRISIS DATA

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An analysis is made of experimental and theoretical data on the influence of the thermophysical properties of the surface material on the film-boiling crisis. Correlations are given for choice of optimum coating thickness. It is shown that the stable film-boiling crisis temperature is linked to the modified Biot number.

In recent years numerous investigations have been published [1-3], in which the film-boiling critical temperature has been found to depend strongly on the thermophysical properties of the heater-surface material. In [3] a theory was put forward to explain this correlation the basis of a two-step heat-transfer model, starting from the premise that the liquid does not wet the wall.

The present article develops this theory and correlates experimental and theoretical data on the influence of the thermophysical properties of the material surface on the film-boiling crisis.

It was shown in [3] that the film-boiling thermodynamic critical temperature depends on oscillations of surface temperature

$$T_{\mathrm{cr}} = T_{\mathrm{lo}} + \Delta T_{\mathrm{w}_0}. \tag{1}$$

If one considers the formal analogy between temperature oscillations of a cooled surface under film-boiling conditions and steady periodic variations in the surrounding-environment temperature, then one can express the amplitude of surface oscillations in the form

$$A_0 \equiv \Delta T_{\mathrm{w}_0} / \Delta T_{\mathrm{cfb}} = f(\mathrm{Bi}^*), \tag{2}$$

where $\Delta T_{\mathrm{cfb}} \equiv (T_{\mathrm{W}} - T_{\mathrm{S}}) \Delta\alpha/\alpha$ is the analog of the amplitude of temperature oscillations of the environment relative to film boiling; $\mathrm{Bi}^* = \alpha/\sqrt{\lambda c \rho \omega}$.

The main objective in analyzing the hydrodynamics of oscillatory motion of the vapor film is to estimate the possible parameters of the oscillatory motion, primarily the frequency of the oscillations.

During oscillatory motion of a liquid and vapor near a heater surface particles are transferred in a direction perpendicular to the surface, and this has a very substantial influence on the heat-transfer mechanism. In spite of the importance of this process for practical applications and for design of certain types of heat exchangers, it has not hitherto been investigated. Analysis of such oscillations is rendered difficult by the fact that the parameters of a boiling two-phase medium are not constant and by the diversity of processes exciting the oscillations. A characteristic feature of these oscillations is that they belong to the class of self-oscillations, i.e., to self-excited oscillations, since they arise in the absence of any kind of periodic forces varying with a known frequency. For a random pulse, under conditions where self-oscillations occur, small motions of a medium or a body take on an oscillatory character, increase up to a specific value, and are maintained due to supply of energy from an external source, which cannot itself acquire oscillatory properties, e.g., heat from a constantly heated surface, or resistance at the interface between two phases. The process of energy transfer to oscillations of the medium can, in turn, depend both on the hydromechanical motion and also on the heat-transfer phenomena. The hydromechanical and thermally induced oscillations differ accordingly [4].

The simplest model for hydromechanical excitation of oscillations in film boiling may be represented as follows. Under the influence of the Archimedean force along a heated wall there is an increase in the flux of vapor which adjoins the wall on one side and the liquid on the other. If the medium interface surface bends at the same point due to random events, the friction at this point increases, and, consequently, this randomly occurring wave on the interface surface begins to grow. The growth of the wave is bounded by stabilizing forces

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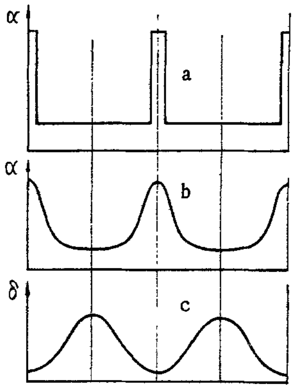

Fig. 1. Relation between variations in the vapor-film thickness (c) and the heat-transfer coefficient (a and b).

of surface tension, by gravity forces, or by other similar forces. But a wind blowing with constant velocity excites waves on the surface of the reservoirs. Here the excitation is linear in nature. For a weak wind no waves are excited at all, but they appear at once when the wind increases above a specific value, and thereafter increase in proportion to any subsequent increase in the wind. The angular frequency ω of gravitational waves is associated with their length l and is given in the form [5]

$$\omega = 2\pi f = \sqrt{2\pi q/l}. \tag{3}$$

It should be noted that a wave with a length greater than the liquid depth is quickly attenuated due to friction at the base, while a wave with a very small amplitude is attenuated more strongly by internal molecular friction. Thus, waves are excited which have a limited length range, depending on the wave amplitude, on the liquid viscosity, and on other factors.

It should be understood that all that has been said, taking account of Eq. (3), refers also to the frequency of the oscillations.

In most cases the governing forces in wave formation are considered to be gravity forces and surface tension. In such cases the angular frequency is given in the form [6]

$$\omega = 2\pi f = \sqrt{\frac{\sigma}{\rho}\left(\frac{2\pi}{l}\right)^3 \pm \frac{2\pi q}{l}}. \tag{4}$$

For Taylor–Helmholtz instability the plus (+) sign refers to the case where the vapor is above the liquid, and the minus (−) sign refers to the case where the liquid is above the vapor. It should be noted that in boiling on a vertical surface, certain forces, analogous to gravity forces, may also act in the horizontal direction, due to various causes (e.g., hydrostatic pressure). When the frequency goes to zero in Eq. (4) and subsequently the previously real values of ω become imaginary, we mean that there is hydromechanical instability of the interface between the media, which usually leads to the medium breaking down into separate sections. From this condition, taking into account the experimentally established fact that the turbulent vapor core is saturated with liquid (a dispersoid), we can estimate the order of magnitude of wavelength for which breakdown of the interface surface occurs. For cryogenic liquids, and also for water, $l_{cr} < 1 \cdot 10^{-2}$ m.

In order to determine the numerical value f of the oscillation frequency we investigated oscillations of surface temperature of a specimen during cooling in liquid nitrogen, oxygen and helium. Analysis of the results showed that the oscillation frequency for local values of temperature on the heat-removal surface of a cooled specimen after immersion in liquid nitrogen, oxygen, and helium was 28–35 Hz. Comparison of the data on frequency of surface-temperature oscillations and frequency of vapor-film oscillations, obtained for a family of liquids differing in thermophysical properties [7], shows that the data exhibit good agreement. One can conclude that the surface temperature in film boiling varies periodically with the vapor-film oscillation frequency. The oscillation frequency depends slightly on the thermophysical properties of the liquid and on the specific heat flux, and when carrying out different types of design estimates one can assume that it is constant and equal approximately to 30 Hz.

Thus, variations in vapor-film thickness lead to variations in local values of heat-removal coefficients, which, in turn, cause fluctuations in surface temperature with a specific frequency. Here there are two possible forms for the variation in heat-removal coefficient: smooth steady-state-periodic and pulse-type (Fig. 1).

TABLE 1. Critical Temperature for Stable Film Boiling as a Function of the Thermophysical Properties of the Specimen Surface

Specimen material	λ, W/m • deg	c, W • h/kg • deg	ρ, kg/m^3	$\mathrm{Bi}^* = \frac{\alpha}{\sqrt{\lambda c \rho \omega}}$	T_{cr}
Steel Kh18N9T	9,5	0,068	7900	0,0175	115
M-3 copper	300	0,056	8930	0,00315	110
FP-734	0,22	0,15	1400	0,167	180
Lead	37,2	0,027	11340	0,0118	113
Melchior	8,5	0,07	8842	0,0172	114
Kovar	14,4	0,1	8340	0,0112	111
Ice	2,7	0,3	926	0,0425	129
Wax	0,075	1,7	960	0,109	150
GF	0,74	0,071	1060	0,162	170

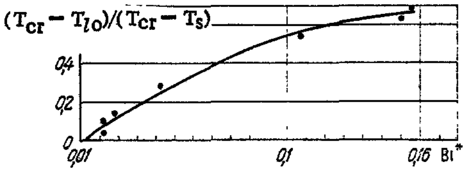

Fig. 2. The critical temperature for stable film boiling as a function of the Bi* number.

A quantitative interpretation of the test data to determine the amplitude of temperature oscillations on the surface and, therefore, of the critical temperature for stable film boiling was based on the formal analogy between reaction of the body surface to change of local heat-removal coefficient in film boiling and the reaction of the body surface to periodic variations in medium temperature during convective heat transfer. For the latter case a mathematical theory has been developed with which one can determine the amplitude of temperature oscillations as a function of the thermophysical properties of the surface [8].

We examined the solutions of certain problems concerning steady-state periodic oscillations of medium temperature and an intermittent heat flux to a body. The basic objectives in the analysis of these solutions are the following:

1) to determine the main parameters and the group arguments governing the response of a cooled object to change under the heat-removal conditions;

2) to estimate the influence of oscillation frequency on the amplitude of wall surface-temperature oscillations;

3) to determine the influence of wall (or coating) thickness of the cooled object on the amplitude of surface-temperature oscillations and cooling rate;

4) to compare the numerical values obtained from the solutions examined in order to correlate the experimental data.

The thermophysical properties assumed for the various materials are given in Table 1. The amplitude of the variation of the heat-removal coefficient was assumed to have two values: $\Delta\alpha = 100$ W/m^2 • deg, which corresponds to a smooth steady-state-periodic variation, and $\Delta\alpha = 1000$ W/m^2 • deg, which corresponds to a sharp increase in heat-removal coefficient during passage of the trough of the wave. The frequency of the vapor-film oscillations and therefore of the heat-removal coefficient is assumed to be 30 sec^{-1}. Simultaneously, in order to verify the possibility of high-frequency oscillations influencing the amplitude of surface-temperature fluctuations, in numerical examples we assumed $f = 1000$ sec^{-1}, which corresponded to the possible time of contact of the liquid with the wall.

In spite of a difference of a factor of two to three in absolute values of the relative amplitude of temperatures oscillations at the forward boundary, calculated for four different boundary-value problems, the solutions obtained allow important conclusions to be made.

Under the conditions examined ($f = 30$ sec^{-1} and $\Delta\alpha = 1000$ W/m^2 • deg) the application of a low-thermal-conductivity coating to a metal leads to an increase in the amplitude of temperature oscillations on the surface by a factor of several tens, and the amplitude reaches a value in excess of 10% of the relative amplitude of oscillations in the coefficient of heat removal from a solid body to the surrounding medium.

The main complex governing the amplitude of temperature oscillations on the surface of an object cooled under film-boiling conditions is the modified Bi* number. The larger the value of Bi*, the larger the amplitude of the surface-temperature oscillations. The experimental data obtained are in satisfactory agreement with theoretical calculations for values $\Delta\alpha = 1000$ W/m²·deg and 30 sec^{-1}. The agreement deteriorates appreciably for the values $\Delta\alpha = 100$ W/m²·deg and $f = 1000$ sec^{-1}. Variation in oscillation frequency in the range 20-50 Hz does not in any way affect the numerical results.

The average value of heat-removal coefficient for a pulsed variation in heat flux

$$\alpha_{av} = \alpha_m \eta_0 + \alpha_0 (1 - \eta_0), \tag{5}$$

where $\alpha_m \cong 1000$ W/m²·deg; $\alpha_0 = 100$ W/m²·deg. For $\eta_0 = 0.042$; $\alpha_{av} = 137$ W/m²·deg; for $\eta_0 = 0.083$, $\alpha_{av} = 175$ W/m²·deg which are in good agreement with experimental data obtained earlier [9].

From the solutions obtained the conclusion was drawn that the coating thickness in most cases should be taken as $\sigma = 0.05$–0.1 mm, since any further increase in coating thickness does not give an appreciable influence in A_0, but leads to an increase in thermal resistance. For a decrease in coating thickness the influence on the amplitude of surface-temperature oscillations decreases.

This conclusion agrees well with ideas as to the nature of excitation of temperature perturbations inside a body [8]. The attenuation coefficient K for the temperature oscillations is related exponentially to the thermal wavelength z:

$$K = \exp(-x\, 2\pi/z). \tag{6}$$

With an accuracy sufficient for engineering purposes (+5%), one can assume that at a depth of $x = 0.5z$ the temperature fluctuations are completely smoothed out.

The experimental data obtained for specimens of various materials and coatings of thickness $x = 0.5z$ can be correlated in the form

$$(T_{cr} - T_{lo})/(T_{cr} - T_s) = f(\mathrm{Bi}^*) \tag{7}$$

and are shown in Fig. 2. It can be seen that the experimental data are in good agreement with ideas as to the nature of the thermodynamic crisis in film boiling.

NOTATION

T, temperature; τ, time; l, length; c, specific heat; λ, specific thermal conductivity; ρ, density; $K = \Delta T_{w_0}/\Delta T_w$, ratio of the absolute values of amplitude of temperature oscillations on the surface and at a depth; δ, thickness; α, heat-removal coefficient; σ, surface tension; η_0, relative time of fluctuations; f, oscillation frequency; x, current coordinate; q, specific heat flux; $z = 2\sqrt{\pi a/f}$, length of thermal wave; a, thermal diffusivity. Indices: lo, limiting overheat; w, wall; w_0, wall surface; c_{fb}, medium relative to film-boiling model; cr, crisis; s, saturation.

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