MINIMUM WALL SUPERHEAT IN FILM BOILING WITH SUBHEATING

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A calculation method is proposed for determining the minimum wall superheat in film boiling at spherical and cylindrical surfaces of a subheated liquid. The results of calculations agree closely with experimental data.

An important characteristic of the film boiling mode, especially in a subheated liquid, is the minimum temperature drop $(t_w - t_s)_{min}$, which determines the lower boundary of stable film boiling. Knowing this quantity $(t_w - t_s)_{min}$ is very important in such problems as determining the conditions of cooling of fuel elements during their emergency flooding with cold liquid upon loss of coolant or in the problem of determining the optimum heat-treatment mode.

Experimental data already available [1-3] indicate that changing the subheat $t_s - t_L$ of the liquid will change the minimum temperature drop $t_w - t_s$ in an almost linear relation, the rate of $t_w - t_s$ increase being maximum at the minimum subheat. For instance, Bradfield's experimental data [2] on film boiling of subheated water at a copper sphere D = 60 mm in diameter indicate that the minimum wall temperature necessary for maintenance of film boiling increases almost linearly with increasing subheat within the given range, the wall temperature rising $\approx 60°C$ as the subheat increases by 10°C. Similar results were obtained in another experimental study [1] of film boiling of water at steel, silver, and copper spheres D = 19 and 25.4 mm in diameter. In those experiments the wall temperature rose approximately 80°C as the subheat of water increased by 10°C. In a study of film boiling of sodium at titanium spheres [3] the minimum wall temperature was found to rise 120°C as the subheat increased by 10°C. Meanwhile, a comparison of these data with the value of $(t_w - t_s)_{min}$ for film boiling of saturated sodium (at $t_s - t_L = 0$) on the basis of experimental data obtained by other authors and on the basis of a theoretical relation [4] indicates that the dependence of $(t_w - t_s)_{min}$ on $t_s - t_L$ appears to be highly nonlinear in the range of small subheat.

The comparison [1] of available experimental data and theoretical relations on $(t_w - t_s)_{min}$ under conditions of film boiling of a subheated liquid indicates an insufficiently close agreement between various proposed relations, best known being the relation proposed by Henry [5] on the basis of unstable wetting of the heater surface by the liquid

$$\frac{(t_w - t_s)_{\min} - (t_w - t_s)_{\min,s}}{(t_w - t_s)_{\min,s} - (t_s - t_L)} = 0.42\left[\left(\frac{\lambda_L \rho_L c_{p,L}}{\lambda_w \rho_w c_{p,w}}\right)^{1/2} \frac{r_V}{c_{p,w}(t_w - t_s)_{\min,s}}\right]^{0.6}, \tag{1}$$

and experimental data.

We will attempt to derive an analytical relation between $(t_w - t_s)_{min}$ and $t_s - t_L$ on the basis of known laws of film boiling.

The minimum temperature drop in film boiling of a saturated liquid is, by definition,

$$(t_w - t_s)_{\min,s} = \frac{q_{\min}}{\bar{\alpha}_V}. \tag{2}$$

In accordance with the mechanism of the physical process of film boiling proposed by Zuber, Linhard, et al. [6], then confirmed by experimental studies, the magnitude of the minimum thermal flux q_{min} is determined by the minimum rate of vapor leaving the vapor film. Unlike in film boiling of a saturated liquid, under conditions of subheating a part of the

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thermal flux is diverted to the liquid through natural convection. Considering that transition from film boiling to bubble boiling is hydrodynamical in nature [6], one can, with sufficient justification, assume that in this case such a transition occurs because the minimum rate of vapor leaving the vapor film has been reached. Consequently, for determining the minimum thermal flux expended on evaporation, this minimum defining the stability limit of film boiling of a subheated liquid, one can use the same relations which apply to a saturated liquid and replace expression (2) correspondingly with the expression

$$(t_w - t_s)_{\min} = \frac{q_{\min}}{\bar{\alpha}_V^{\text{sub}}}. \tag{3}$$

Using the Zuber relation between minimum and maximum thermal fluxes [7]

$$\frac{q_{\min}}{q_{\max}} \simeq \left(\frac{\rho_V}{\rho_L}\right)^{1/2} \tag{4}$$

and the relations [8] for the maximum thermal flux q_{max} in boiling of a saturated liquid at a horizontal cylinder or sphere, we have for the minimum thermal flux q_{min}

$$q_{\min} = \left(\frac{\rho_V}{\rho_L}\right)^{1/2} q_{\max}. \tag{5}$$

It has been demonstrated in another study [9] that as the degrees of subheat increase, while all other conditions remain the same, both the evaporation rate and the thermal flux carried away by the vapor decrease exponentially. In that study a relation describing the heat-transfer coefficient to a vapor film for evaporation of a subheated liquid by film boiling

$$\bar{\alpha}_V^{\text{sub}} = q_V/(t_w - t_s) = \bar{\alpha}_V \exp\left[-\frac{\bar{\alpha}_{\text{n.c.}}(t_s - t_L)}{\bar{\alpha}_V (t_w - t_s)}\right] \tag{6}$$

has also been obtained. The heat-transfer coefficient α_V for film boiling of a saturated liquid at a sphere or horizontal cylinder under conditions of natural convection can be determined from the relations in studies [6, 10].

A relation has also been obtained [9] for the heat-transfer coefficient to a subheated liquid in film boiling in a large pool, namely

$$\bar{\alpha}_{\text{n.c.}} = \begin{cases} 0{,}47 \dfrac{\lambda_V}{D} \Pi^{1/4} & \text{for } \Pi \leqslant 3 \cdot 10^8; \\ 0{,}1 \dfrac{\lambda_V}{D} \Pi^{1/3} & \text{for } \Pi > 3 \cdot 10^8, \end{cases} \tag{7}$$

where

$$\Pi = N_{Gr} \left(\frac{\nu_V}{\nu_L}\right)^2 \left(\frac{c_{p,V}(t_w - t_s)}{c_{p,L}(t_s - t_L)}\right) \left(\frac{\rho_V \mu_V}{\rho_L \mu_L}\right) \left(\frac{N_{Pr_L}}{N_{Pr_V}}\right) N_{Pr_L}^{3/2}.$$

The thermophysical properties of the liquid and the vapor in a film are determined at the respective temperatures $\bar{t}_V = 0.5(t_w + t_s)$ and $\bar{t}_L = 0.5(t_s + t_L)$.

From relations (3) and (6) we obtain the condition under which the dependence of $(t_w - t_s)_{min}$ on $t_s - t_L$ can be established, namely

$$q_{\min} = \bar{\alpha}_V (t_w - t_s)_{\min} \exp\left[-\frac{\bar{\alpha}_{\text{n.c.}}(t_s - t_L)}{\bar{\alpha}_V (t_w - t_s)_{\min}}\right]. \tag{8}$$

This condition can be expressed as

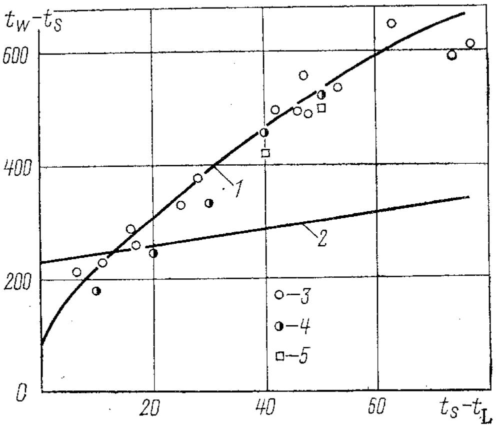

Fig. 1. Comparison of experimental and theoretical data on the minimum wall superheat: 1) relation (10); 2) relation (1); 3-5) film boiling of water; 3) data [2] pertaining to chromium-copper spheres 59.7 mm in diameter; 4) data [1] pertaining to steel spheres 25.4 and 19 mm in diameter, copper and silver spheres 19 mm in diameter; 5) data [1] pertaining to inductively heated steel spheres 19 mm in diameter; $(t_W - t_S)$ and $(t_S - t_L)$ in °C.

$$t_s - t_w = \frac{\bar{\alpha}_V}{\bar{\alpha}_{n.c}} (t_w - t_s)_{\min} \ln \frac{\bar{\alpha}_V (t_w - t_s)_{\min}}{q_{\min}}. \quad (9)$$

The quantity $\bar{\alpha}_V$ in expression (9) can be determined from the relations in studies [6, 10], while q_{min} and $\bar{\alpha}_{n.c.}$ can be determined from relations (5) and (7), respectively

For simplifying the calculations, we will transform expression (9) by inserting into it the relation for $\bar{\alpha}_{n.c}$ and extracting the complex $(t_W - t_S)_{min}/(t_S - t_L)$ from the expression for parameter Π. As a result, we finally obtain

$$t_s - t_L = (t_w - t_s)_{\min} \left[\frac{\bar{\alpha}_V}{A} \ln \frac{\bar{\alpha}_V (t_w - t_s)_{\min}}{q_{\min}} \right]^k, \quad (10)$$

where

$$A = \bar{\alpha}_{n.c.} \left(\frac{t_s - t_L}{(t_w - t_s)_{\min}} \right)^{\frac{k-1}{k}}; \quad k = \begin{cases} 4/3 & \text{for } \Pi \leqslant 3 \cdot 10^8; \\ 3/2 & \text{for } \Pi > 3 \cdot 10^8. \end{cases}$$

Inasmuch as the thermophysical properties of the liquid which appear in the expression for A as well the exponent k depend on the degrees of subheat of the liquid, calculations according to expression (10) are performed iteratively. In the first approximation with $(t_W - t_S)_{min}$ given one can let $\Pi \geqslant 3 \cdot 10^8$, then stipulate the thermophysical properties of the liquid in the expression for A at the saturation temperature and then determine $t_S - t_L$ from expression (10). In subsequent approximations for calculations according to expression (10) one can use the values of $t_S - t_L$ obtained in preceding approximations. Usually the second approximation already yields the magnitude of $t_S - t_L$ with sufficient engineering accuracy.

The dependence of $(t_W - t_S)_{min}$ on the degree of subheat $t_S - t_L$ during film boiling was calculated according to expression (10) for subheated water at the same spheres of studies [1, 2] under atmospheric pressure and conditions of natural convection. The results of a comparison indicate a close agreement between these calculations and the experimental data [1, 2] (Fig. 1). The minimum temperature drop $(t_W - t_S)_{min}$ depends nonlinearly on the subheat. The rate of increase of $(t_w - t_s)_{min}$ is, moreover, faster in the range of small subheat than in the range of large subheat. Within the range of film boiling of water with 10-70° subheat, however, the dependence of $(t_w - t_s)_{min}$ on $t_s - t_L$ can, as earlier [1, 2], be approximated with a linear relation (Fig. 1).

NOTATION

a, thermal diffusivity; c_p, specific heat; D, diameter; g, gravitational acceleration; $N_{Gr,v} = (gD^3/\nu_V^2)(\rho_L - \rho_V)/\rho_V$; $N_{Pr} = \nu/a$; i, enthalpy; q, specific thermal flux; r_V, heat of evaporation; t, temperature; $\bar{\alpha}$, mean heat-transfer coefficient; λ, thermal conductivity; μ, dynamic viscosity; ν, kinematic viscosity; ρ, density; and σ, coefficient of surface tension. Subscripts: L, liquid; max, maximum; min, minimum; sub, subheat; V, vapor; n.c., natural convection; w, wall; and s, saturation line; prime sign, liquid at saturation line.

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