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IMPROVED PREDICTION OF CRITICAL HEAT FLUX IN LIQUID METAL POOL BOILING

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IMPROVED PREDICTION OF CRITICAL HEAT FLUX IN LIQUID METAL POOL BOILING

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Abstract

The Kutateladze criterion for the pool boiling critical heat flux, which works well for nonmetallic liquids at or above atmospheric pressure, fails for the alkali liquid metals in the pressure range of interest for Liquid Metal Fast Breeder Reactor applications. In this pressure range bubble growth of the alkali liquid metals is largely inertia-controlled, in view of the large thermal conductivities, which implies a significant condensing heat flux within the bubbles themselves. The bubble growth is assumed to be described by the Mikic, Rohsenow, and Griffith equation. In this way a mean bubble age is determined, and hence a mean bubble thermal boundary layer thickness. The time-average critical heat flux is then obtained as the sum of the Kutateladze flux and the flux due to condensation on the bubble surfaces. No empirical parameters are employed. The present analysis predicts critical heat fluxes lying generally within the data band.

NOMENCLATURE

- a : Empirical constant, Eq. (3)
- A : Parameter grouping, Eq. (6), m/hr
- b : Analytical constant, Eq. (6), dimensionless
- B : Parameter grouping, Eq. (5) ff, m/hr$^{1/2}$
- C_f : Liquid specific heat, kcal/kg°K
- C_1 : Empirical constant, atm
- C_D : Drag coefficient, dimensionless
- D : Bubble diameter, m
- g : Gravitational constant, m/hr^2
- h : Mean heat transfer coefficient, kcal/m^2°K
- h_{fg} : Latent heat of vaporization, kcal/kg
- k_f : Thermal conductivity, kcal/mhr°K
- K : Kutateladze constant, Eq. (1), dim.
- m : Empirical constant, Eq. (13), dim.
- M : Molecular weight
- N_J : Jakob number, dim.
- Pr : Reduced pressure, dim.
- q_c : Condensing heat flux, kcal/m^{2}hr
- q_K : Critical heat flux, Eq. (1), kcal/m^{2}hr
- q_t : Total heat flux, kcal/m^{2}hr
- R : Bubble radius, m
- R^+ : Dimensionless bubble radius, Eq. (5)
- R_g : Gas constant
- t : Time, hr
- t^+ : Dimensionless time, Eq. (5)
- t_b : Mean bubble age, hr
- t_d : Departure time, hr
- T : Temperature, °K
- ΔT_s : T_w-T_s, wall superheat, °K
- α_f : Liquid thermal diffusivity, m^2/hr
- δ_f : Bubble thermal boundary layer thickness, m
- ϵ : Accommodation coefficient, dim.
- η : Temperature ratio, Eq. (8)
- ρ : Density, kg/m^3
- σ : Surface tension, kg/m

Subscripts

- f : Liquid
- g : Gas
- s : Saturation
- t : Total
- v : Vapor

INTRODUCTION

For ordinary fluids, such as water or organic liquids, at atmospheric pressure and above, the Kutateladze equation has been reasonably successful in predicting the critical (or maximum) heat flux in pool boiling from a horizontal heating surface (1). This expression is of the form

$$\frac{q_K}{h_{fg}(\rho_g g)^{1/2}\,[\sigma(\rho_f - \rho_g)]^{1/4}} = K \tag{1}$$

a constant, which for heater diameters large compared to the capillary wave length, takes on the value K = 0.14-0.16 in order to fit the experimental data. It is seen that the Kutateladze number, K, determines the mean vapor velocity leaving the surface, provided it is assumed that all the heat flux, q_K, from the heater surface is used to vaporize liquid at the saturation temperature:

$$q_K \simeq h_{fg}\,\rho_g\,u_g \tag{2}$$

where u_g is the mean vapor velocity normal to the surface. There thus appears to be a critical normalized vapor velocity at which flooding commences, so that liquid can no longer easily penetrate to the heating surface.

Since the latent heat, surface tension and liquid density are slowly varying functions of the saturation temperature, Eq. (1) predicts that the critical heat flux increases approximately as the square root of the pressure. For water below 0.2 atm or for alkali liquid metals below 2 atm, the dependence is much less marked, the exponent in the pressure dependence being closer to 0.1 than 0.5. One notes that this change in exponent coincides roughly with the appearance of inertia-controlled, rather than of diffusion-controlled, bubble growth. This implies that the pressure within the growing bubbles is no longer essentially the saturation pressure, but is time-dependent, lying between the vapor pressures at the wall and saturation temperatures. For such bubbles internal mass transfer effects are significant, evaporation occurring from the lower regions of the bubble and condensation on the cooler polar regions. This condensation reduces the effective vapor velocity leaving the surface, which must be taken into account in computing the critical heat flux by the Kutateladze criterion. In this note a simplified physical model is employed. Nevertheless, the resulting critical heat flux predictions lie generally in the data band in the pressure range of interest for Liquid Metal Fast Breeder Reactor applications.

FORMULATION OF THE PROBLEM

It is known that rapidly growing bubbles tend to assume a flattened (hemispherical) shape while attached to the heating surface. For a well-wetted surface, such as with stainless steel in a sodium pool, a thin liquid microlayer persists between the bubble and the solid surface, whose evaporation supplies much of the vapor for bubble growth. However, for liquid metals the thermal resistance of this microlayer is very small, and may be lumped with the wall resistance. There will also be a gas-phase thermal resistance, due to nonequilibrium effects, which will, however, be small unless the accommodation coefficient, ϵ, is substantially less than unity. In theory, one could determine the time-and-space-varying wall surface temperature under the growing bubble by a consideration of the conservation equations for the bubble, the solid substrate, and the surrounding liquid.* However, our present interest is simply to determine the mean wall superheat, given indirectly by a generalized correlation due to Subbotin et al. (2)

$$h = a\left(\frac{k_f h_{fg}\rho_g}{\sigma T_s^{\,2}}\right)^{1/3} (p_r)^b\,(q_t)^{2/3} \tag{3}$$

where, for reduced pressures, p_r, between 4×10^{-5} and 10^{-3}, a = 8 and b = 0.45, while for $10^{-3} < p_r < 2 \times 10^{-2}$, a = 1 and b = 0.15.

The wall superheat is then related to the mean wall heat flux by

$$q_t = h(T_w - T_s) = h\Delta T_s \tag{4}$$

It is assumed that the nonevaporative component of the wall surface heat flux is small compared to the heat removal by vaporization into the growing bubbles. At high vacua, however, one would expect this assumption no longer to hold, in view of the very low volumetric heat content of the vapor. Furthermore, conductive heat transfer between the bubbles would be expected to be more significant with low Prandtl-number fluids then with ordinary fluids.

To estimate the condensing heat flux, it is first necessary to determine the growth rate of a bubble attached to a heating surface operating at the critical heat flux. No experimental data are available for this case, either for nonmetallic or metallic liquids. It is known, however, that in this pressure range inertial effects are quite important in the bubble growth. One approach is to assume the validity of the combined inertial-diffusive equation given by Mikic, Rohsenow, and Griffith (3) for a bubble growing in an initially uniformly-superheated liquid:

$$R^+ = \frac{2}{3}\left[(t^+ + 1)^{3/2} - (t^{+3/2} + 1)\right] \tag{5}$$

where

$$R^+ = \frac{AR}{B^2}\ ;\ t^+ = \frac{A^2 t}{B^2}\ ;\ B = \left(\frac{12\alpha_f}{\pi}\right)^{1/2} N_J;$$

and N_J is the Jakob number, based on the wall superheat. Here

$$A^2 = \frac{b h_{fg}\rho_g \Delta T_s}{\rho_f T_s} \tag{6}$$

The Jakob number is given by

$$N_J = \frac{\rho_f C_f \Delta T_s}{h_{fg}\rho_g} \tag{7}$$

For a spherical bubble attached to a solid wall with zero contact angle, b = $\pi/7$, while in the absence of solid walls, b = 2/3. We choose here b = 2/3, in view of the fact that the hemispherical bubble shape, at high growth rates, tends to preserve spherical symmetry within the liquid half-space. Equation (5) may be viewed as an interpolative equation. Defining

$$\eta = \frac{T_v - T_s}{T_w - T_s},\ 0 \le \eta \le 1, \tag{8}$$

Equation (5) reduces to the Rayleigh solution for inertia-controlled bubble growth as $\eta \to 1$, and to the limiting Plesset-Zwick equation for diffusion-controlled bubble growth (4) as $\eta \to 0$. For combined inertia and diffusion effects, it has been shown to be in very good agreement with the exact solution.

To estimate the condensing heat flux, we note that the thermal resistance to the heat flow consists of a gas-phase (nonequilibrium) resistance in series with a liquid-phase boundary layer resistance at the bubble wall. Assuming spherical symmetry for the flow fields for heat and mass, the condensing heat flux takes the form

$$q_c = \frac{T_v - T_s}{\dfrac{\delta_f}{k_f} + \sqrt{\dfrac{2\pi R_g T_v}{M}}\left(\dfrac{T_s}{\epsilon h_{fg}^2\rho_g}\right)} \tag{9}$$

where the temperature of the vapor, T_v, is assumed to be a function of time only. The thermal boundary layer thickness, δ_f, is given by the limiting expression:

$$\delta_f = \sqrt{\pi\alpha_f t_b} \tag{10}$$

* This work has, in fact been done (7), and will be reported elsewhere.

where the characteristic time, t_b, is chosen to be the mean age of bubbles attached to the wall.

It will be recognized that the differential form of the Clausius-Clapeyron equation has been employed in computing the gas-phase resistance term. This term is small compared to the liquid-phase resistance unless traces of noncondensible gases are present, which tend to build up in a concentration boundary layer near the condensing surface and hence drastically reduce the effective accommodation coefficient, ε. Similarly, ε will be reduced if solid impurities, such as dissolved oxides, accumulate as a thin layer at the liquid-vapor interface.

It is now possible to calculate the mean bubble age, t_b, from Eq. (5) and an estimate of the bubble departure radius. From a balance of buoyant, drag and acceleration forces on the bubble at departure, Roll and Myers (5) devised the equation:

$$\frac{\pi D^3}{6} g(\rho_f - \rho_g) - \frac{C_D \pi D^2 \rho_f \dot{D}^2}{8} - \frac{\pi D^3 \rho_f}{12} \left(1 + \frac{3}{8}\right)\ddot{D} = 0 \qquad (11)$$

where the drag coefficient, C_D, is here taken to be unity. Mamontova (6) has given a correlation for potassium bubble departure diameters at low pressures (as reported in Ref. 2) which reduces to the form of the first two terms of Eq. (11). By writing this equation in dimensionless form, it can be solved by differentiation and substitution from Eq. (5) to give t_d, the bubble departure time, assumed to be twice t_b. The mean condensing heat flux is then obtained from Eqs. (9) and (10).

Noting that the hemispherical bubble surface area is at all times twice its base area, one finally obtains a corrected estimate of the time-mean heat flux

$$q_t = q_K + 2q_c \qquad (12)$$

This states that the evaporative heat flow from the wall, averaged over many bubbles, is reduced by vapor condensation, so that the net vapor velocity for flooding, given by Eqs. (1) and (2), is less than the mean velocity of vapor leaving the wall.

RESULTS

The corrected critical heat flux, q_t, calculated as a function of system pressure for sodium, potassium, cesium and rubidium, is shown in Figs. (1) - (4). The experimental data for these systems, taken with horizontal plate and tubular heaters in a liquid-metal pool, have been taken from Ref. (2). These same authors have given a generalized correlation for the critical heat flux for alkali liquid metals:

$$q_t = \left[1 + \frac{C}{P_{cr}} \frac{F_s}{P_{cr}}\right]^m K h_{fg} (g\rho_v)^{1/2} [\sigma(\rho_f - \rho_v)]^{1/4} \qquad (13)$$

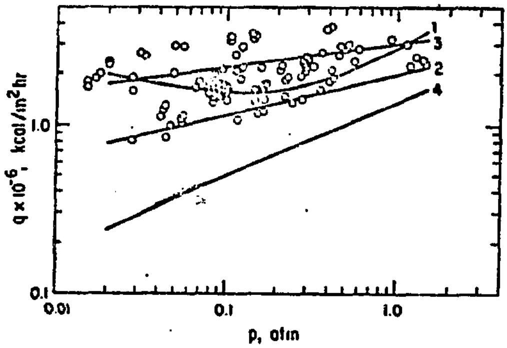

Fig. 1 Critical Heat Flux in Pool Boiling of Sodium vs Pressure (Data from Ref. 2); 1 - this work, 2 - Subbotin *et al.* C = 18, 3 - Subbotin *et al.* C = 45, and 4 - Eq. (1).

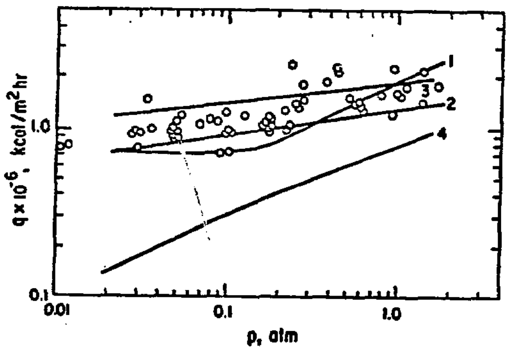

Fig. 2 Critical Heat Flux in Pool Boiling of Potassium vs Pressure (Data from Ref. 2); 1 - this work, 2 - Subbotin *et al.* C = 18, 3 - Subbotin *et al.* C = 45, and 4 - Eq. (1).

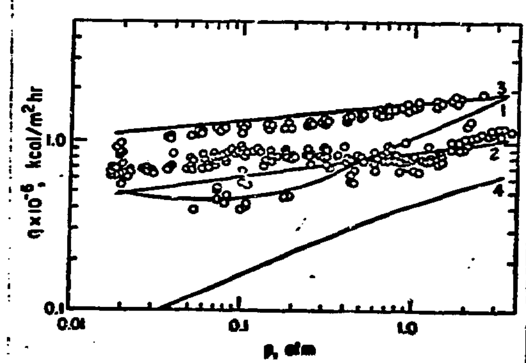

Fig. 3 Critical Heat Flux in Pool Boiling of Cesium vs Pressure (Data from Ref. 2); 1 - this work, 2 - Subbotin *et al.* C = 18, 3 - Subbotin *et al.* C = 45, and 4 - Eq. (1).

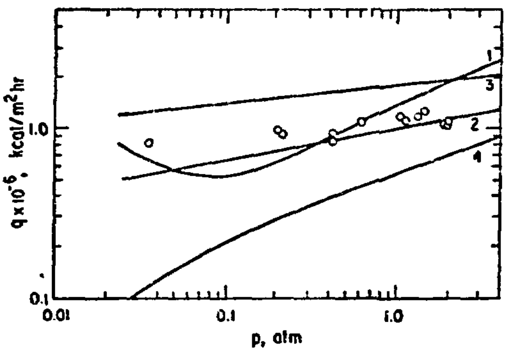

Fig. 4 Critical Heat Flux in Pool Boiling of Rubidium vs Pressure (Data from Ref. 2); 1 - this work, 2 - Subbotin et al. C = 18, 3 - Subbotin et al. C = 45, and 4 - Eq. (1).

where for developed (stable) boiling C = 45 atm, but C = 18 atm for unstable boiling. The Kutateladze number K is taken to be 0.14, and m = 0.4. These curves are also shown in Fig. 1-4. At the pressures of interest (0.1-2 atm), the corrected flux lines lie generally within the data band. This is in contrast to the Kutateladze equation, which is low by a factor of 3-5 in this pressure range. It should be emphasized once again that no empirical parameters have been introduced into these calculations. Caution should be exercised, however, in extrapolating these results to higher or lower pressures. In particular, we note that the Mikic et al., equation is not established experimentally for liquid-metal bubble growth on surfaces; bubble departure data at critical heat flux conditions are lacking; bubble population densities have not been measured, so that it is not yet possible to estimate the nonevaporative component of heat transfer to the liquid between the bubbles; and the thickness of the thermal boundary layer in the liquid next to the wall prior to the appearance of a bubble has not been measured. Nevertheless, the present approach seems to indicate correctly the major contributions to the liquid-metal critical heat flux.

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