GENERALIZATION OF THE EXPERIMENTAL DATA ON EXTENDED CRISIS IN HEAT TRANSFER IN THE BOILING OF A LIQUID

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ABSTRACT: A generalized formula is given for the critical heat flux, and it is shown that crises of this type are most characteristic of the boiling of organic liquids at high temperatures.

NOTATION

q_*—critical heat flux;
q—heat flux;
W—mean flow speed of liquid in crisis section;
W_g—mass flow rate;
r—latent heat of evaporation;
σ—coefficient of surface tension;
ρ"—density of dry saturated vapor;
ρ'—density of liquid on saturation line;
i'—enthalpy of liquid on saturation line;
i—mean enthalpy of liquid in crisis cross section;
c_f—coefficient of friction;
g—acceleration due to gravity;
P—static pressure in crisis cross section;
T'—saturation temperature;
T_*—temperature of surface of tube;
ρ—mean density of liquid in crisis cross section.

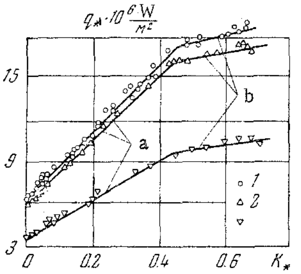

Fig. 1. Relation of q_* to K_* for P = = 30 · 10^5 N/m^2. Points 1, 2, and 3 correspond to W_g of 25 · 10^3, 22 · 10^3, and 11· 10^3 kg/m^{2}sec.

The critical heat flux increases with the difference of the actual liquid temperature from the saturation temperature, and particularly large differences are possible for high-boiling organic liquids. Experiment [1-3] shows that the dependence of q_* on this difference d for these is rather different from the curves for liquids such as alcohol and water.

Studies [4, 5] of the boiling of ethanol in tubes show that there are two crisis mechanisms; one of these (called normal crisis) has q_* increasing rapidly with d (line a in Fig. 1), and this always gives rise to a hot spot directly in the region of the exit edge, i.e., where d is least.

The interpolation formula for the normal crisis for 0 < W < ∞ takes [4-6] the form

$$\frac{q_*}{1+K_{**}} = k_* r W \sqrt{\rho\rho''} + kr\sqrt{\rho''}\sqrt[4]{g^2\sigma(\rho'-\rho'')}. \qquad (1)$$

Calculations [7] give

$$\frac{\pi}{8\sqrt{2\pi}3^{1/4}} < k < \frac{\pi}{8\sqrt{2\pi}}.$$

Data [5, 6] give

$$k_* \approx 2c_f\left(1-\frac{\pi}{4}\right)\frac{\pi}{4}, \quad K_* = \frac{i'-i}{r}, \quad K_{**} = \frac{i'-i}{r}\frac{\sqrt{\rho}}{\sqrt{\rho''}}.$$

Criterion K_{**} was first derived empirically in [1].

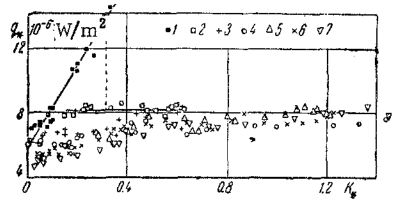

Fig. 2. Dependence of q_* on K_* when a persistent deposit is formed; the points are numbered in the order in which the tests were done. Point 1 (before formation of deposit) corresponds to P = 30 · 10^5 N/m^2 and W_g = 23 · 10^3 kg/m^2·sec; the other points in the same units are: 2—(60 · 10^5, 23 · 10^3), 3—(40 · 10^5, 23 · 10^3), 4—(51 · 10^5, 10 · 10^3), 5—(51 · 10^3, 13 · 10^3), 6—(51 · 10^5, 22 · 10^3) 7—(40 · 10^5, 13 · 10^3)

The second crisis process occurs only for d large and has q_* very weakly dependent on d (line b), which means that a relatively large part of the heated length becomes overheated simultaneously. Often the restricted length of the heated tube (l/d = 15 in our experiments) caused the reddening to set in at the start or middle of the experimental section, and this has led to the use of the term generalized crisis [4, 5].

The data show that q_* in generalized crisis is governed principally by the pressure and the flow speed, being independant of time and the sequence in which the tests are done. Generalized crisis differs essentially from overheating arising from a persistent deposit due to thermal decomposition of the organic liquid or to other causes. Figure 2 shows that the limiting heat flux ceased to be dependent on the pressure and velocity once such a deposit had been produced during normal crisis; thereafter it gradually decreased from run to run. Examination of the inner surface revealed a dense black deposit; normal and generalized crises could again be produced once this had been removed.

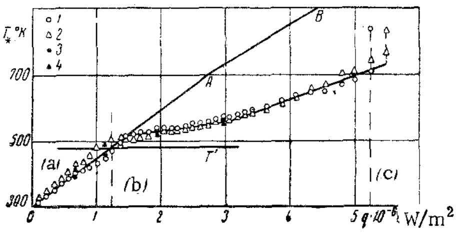

Fig. 3. Relation of T_* to q, with q initially increased: 1) T_* at outlet, 2) T_* at inlet; q reduced for subsequent measurements, 3) T_* at outlet, 4) T_* at inlet. Part b corresponds to the production of sound, and part c to occurrence of light.

We performed tests with ethanol at $15 \cdot 10^5$ N/m^2 and a flow speed of 6 m/sec in order to examine conditions in generalized crisis at high d. The tube was of stainless steel: internal diameter 4 mm, wall thickness 1 mm, length of heated part 60 mm. The apparatus has already been described [4, 5]. The temperatures 10 mm from the inlet and outlet on the outside of the tube were measured with chromel-alumel thermocouples insulated with mica and asbestos.

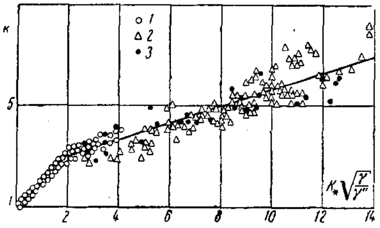

Fig. 4. Points: 1) ethanol boiling in a tube [4, 5]; 2) monoisopropyldiphenyl boiling in a tube [2, 3]; 3) Dowtherm boiling on a plate exposed to a flow [1] $K = q_*/krW\sqrt{\rho\rho''} + kr\sqrt{\rho''}\sqrt[4]{g\sigma(\rho' - \rho'')}$.

The temperature on the inner surface was found by adding the temperature drop in the wall, which was calculated.

Figure 3 shows the temperature of the inner surface as a function of heat flux. Part ab corresponds to convective heat transfer without boiling; in bc there is a bubbling of the surface layers, which as a whole are not heated to the saturation point, this being accompanied by a characteristic noise. To the right of line c the wall temperature rises spontaneously at constant heat flux, which was taken as the onset of crisis. The curve of Fig. 3 was highly reproducible.

It appears that the two types of crisis are physically related, since there is a continuous transition from the $q_*(K_*)$ for the one to that for the other, the crises also being highly reproducible. Both crises arise from loss of hydrodynamic stability of the two-phase boiling layer. In this case the q_* for the generalized crisis must be determined by a system composed of the criteria in (1), i.e., by the equation

$$F(k,\ k_*,\ K_{**}) = 0. \qquad (2)$$

The data for various pressures and speeds showed that the point of intersection of parts a and b of the $q_*(K_*)$ curves always corresponds to $K_{**} \approx 2$. This result for $K_{**} \approx 2$ enables us to find the velocity dependence of q_* in (2),

$$K = \frac{q_*}{k_* rW\sqrt{\rho\rho''} + kr\sqrt{\rho''}\,[g^2\sigma(\rho' - \rho'')]^{1/4}} = 3\,[a + f(K_*)]. \qquad (3)$$

Figure 4 shows my experimental data for ethanol and the data of [2, 3] for monoisopropyldiphenyl, both for liquid in tubes. The line of lesser slope fits

$$\frac{q_*}{2.5(1+0.12K_{**})} = k_* rW\sqrt{\rho\rho''} + kr\sqrt{\rho''}\,[g^2\sigma(\rho' - \rho'')]^{1/4}. \qquad (4)$$

Figure 4 also shows the experimental points of [1] for the crisis in Dowtherm on a plate with liquid flowing over it. Here the c_f for (4) is substantially different from that for flow of a liquid in a tube, since it is calculated from the formula for a turbulent boundary layer on a plate with allowance for the turbulence produced by a leading edge of finite thickness [formula (11.6) or [8]].

The points agree well, in spite of the widely differing flow conditions, which confirms the assumption about the hydrodynamic nature of the generalized crisis.

Figure 4 shows that there are two relationships of q_* to d. The first occurs for $K_{**} \le 2$, where the slope is high, this being characteristic mainly of boiling crises for ordinary liquids (water, ammonia, alcohols, saturated hydrocarbons) of relatively low boiling point. On the other hand, most of the data for high-boiling organic compounds are for $K_{**} \gg 2$ (region of generalized crisis), on account of the high boiling points at low pressures.

These two $q_*(K_{**})$ relationships do not rule out the existence of others for q_* at very small or very large K_*; the results of [3] for very large values indicate a dependence of q_* on K_* even less marked than that for the generalized crisis, but the inadequate quantity of experimental data makes it impossible to derive the relationship with certainty.

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