HEAT-TRANSFER CRISIS IN THE BOILING OF LIQUIDS ON MICROSURFACES

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Data is presented on the effect of the dimensions of heaters on the heat-transfer crisis during boiling in a large volume. Relations are obtained to calculate the kinetic loads in the boiling of liquids on microsurfaces.

It has now been established experimentally [1-3] that in the boiling of liquids on microsurfaces (MS), the nucleate boiling regime extends to heat-flux values several times greater than the critical values for boiling on lengthy surfaces. An increase in the load leads to a smooth transition from the nucleate regime to unstable boiling. This transition complicates the experimental determination of $q_{cr.ms}$ on MS.

This article presents results of a study conducted to determine the critical heat fluxes in the boiling of water, ethanol, and liquid organofluorine dielectrics (MD-3F, DEF, PFP) on horizontal MSs 0.4-5.0 mm in diameter in a large volume. The studies were conducted at the saturation temperature of the liquids. Figure 1 schematically depicts the design of the test element. A high-temperature rod 1 (copper) was glued into a load-bearing wall 2 made of a material (fiberglass) with a low thermal conductivity. Constantin conductors soldered into the heat conductor 1, together with the rod, made up copper—constantin thermocouples T_1 and T_2. We used the readings of these thermocouples to determine the heat flux Q_{sup} supplied to the end. Thermocouples T_3-T_6 were embedded in load-bearing wall 2. We used these thermocouples and the solution of the inverse heat-conduction problem to determine the heat flux from the rod to the load-bearing wall and thence to the liquid Q_p. The heat flux Q_{rem} removed from the MS was determined as the difference between Q_{sup} and Q_p. A more detailed description of the design of the test element and the method used to determine the experimental data was presented in [1, 2].

The critical heat flux $q_{cr.ms}$ was determined from the function $\alpha = f(q_{rem})$ upon attainment of the maximum value of the heat-transfer coefficient α_{max}. The point of inflection on the curve corresponded to the value of $q_{cr.ms}$. We thus found $qa_{cr.ms}$ for each MS diameter. We noted in the tests that the radius of the MS, R_{ms}, has an effect on $q_{cr.ms}$. Meanwhile, the values of $q_{cr.ms}$ increase with a decrease in R_{ms}.

In accordance with hydrodynamic crisis theory [4-7], the value of q_{cr} on any heater of finite dimensions will be determined by the configuration of the jets leaving the surface. The geometry, cross section, and number of jets depend on the form and dimension of the

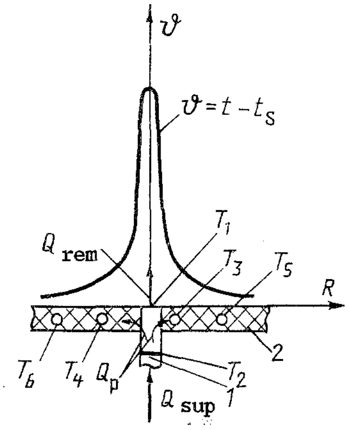

Fig. 1. Sketch of test element and the distribution of the temperature field in it: 1) heat conductor (the end is the microsurface); 2) low-temperature load-bearing wall; T_1, T_2, thermocouples to determine the supplied heat flux Q_{sup}; T_3-T_6, thermocouples to determine the heat flux propagating to the load-bearing wall Q_p.

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heater. A boiling crisis begins when the rising vapor jets become unstable. In this case, the limiting vaporization rate will be [4-6]:

$$\frac{q_{\mathrm{cr}}}{r\rho''} = W_{\mathrm{cr}} \frac{S}{F_{\mathrm{h}}}, \tag{1}$$

where S is the cross-sectional area of the vapor jets leaving the surface F_h; r is the heat of vaporization; ρ" is the density of the vapor; W_{cr} is the critical velocity of the vapor in the jet:

$$W_{\mathrm{cr}} = \sqrt{\frac{2\pi\sigma}{\rho'' l_{\mathrm{i.cr}}}}; \tag{2}$$

σ is surface tension; $l_{\mathrm{i.cr}}$ is the most sensitive wavelength associated with Taylor instability:

$$l_{\mathrm{i.cr}} = 2\pi \sqrt{3\sigma/g(\rho' - \rho'')}; \tag{3}$$

ρ' is the density of the liquid; g is acceleration due to gravity.

On horizontal heaters, the distance between surfacing vapor jets is $l_{\mathrm{i.cr}}$. Thus, for water, the distance between jets should be 27 mm. It should be 16 mm for ethanol and should not exceed 10 mm for organofluorine dielectrics. The dimensions of the MS's we studied were significantly smaller than $l_{\mathrm{i.cr}}$, so we saw only one vapor jet in our tests. Similar values were obtained when we compared the velocity of the vapor in the jet according to Eq. (2) and the velocity calculated from filming of liquid DEF (for example) in the film boiling regime. Thus, W_{cr} = 0.77 m/sec according to Eq. (2), while according to the film the rate of ascent of the vapor cloud was equal to 0.72 m/sec. Thus, the cross section of the separating vapor structures was proportional to the capillary constant l_c, by analogy with the separation diameters of individual vapor bubbles. The area of the heater F_h in the given case was proportional to the radius of the MS R_{ms}. Inserting Eq. (2) together with (3) into (1), we obtain

$$q_{\mathrm{cr.ms}} = 0{,}77 r \sqrt{\rho''} \sqrt[4]{\sigma g(\rho' - \rho'')} \frac{S}{F_{\mathrm{h}}}. \tag{4}$$

Equation (4) yields an inversely proportional dependence of $q_{\mathrm{cr.ms}}$ on the dimensions of the MS. Having divided (4) by $q_{\mathrm{cr}\infty}$ found from the formula derived by Kutateladze [7], we obtain

$$q_{\mathrm{cr.ms}}/q_{\mathrm{cr}\infty} = 5{,}9\, S/F_{\mathrm{h}}. \tag{5}$$

The cross section of the surfacing vapor jets above the MS is fairly difficult to determine. Thus, on the basis of the considerations noted above, we can represent Eq. (5) in the form

$$q_{\mathrm{cr.ms}}/q_{\mathrm{cr}\infty} = C(l_{\mathrm{c}}/R_{\mathrm{ms}})^n. \tag{6}$$

By comparing the experimental data, we find an equation to calculate $q_{\mathrm{cr.ms}}$ as a function of the dimensions of the MS:

$$q_{\mathrm{cr.ms}} = 3q_{\mathrm{cr}\infty}(R_{\mathrm{ms}}/l_{\mathrm{c}})^{-0{,}65}. \tag{7}$$

This relation satisfactorily generalizes both our experimental data and the data in [8-10] with a scatter of ±20% (Fig. 2). It is evident from Fig. 2 that the values of $q_{\mathrm{cr.ms}}$ lie considerably above lines I and II in the case of boiling on cylinders and spheres. The size of the heat-transfer surface affects $q_{\mathrm{cr.ms}}$ only up to values of the simplex R/l_c = 8. A further increase in the dimensions of the heating surfaces has no effect on q_{cr}, which is evidence of the transition of the surface to an extended area.

Similar results are obtained if the description of the boiling crisis is approached by the method proposed in [11].

The smooth transition from nucleate to film boiling is evidence of a continual increase in the number of vaporization centers on the MS. When a certain limiting number of vaporization centers are present, the rate of heat transfer on the MS reaches its maximum value. Vapor bubbles growing at the edge of the MS begin to impede horizontal movement

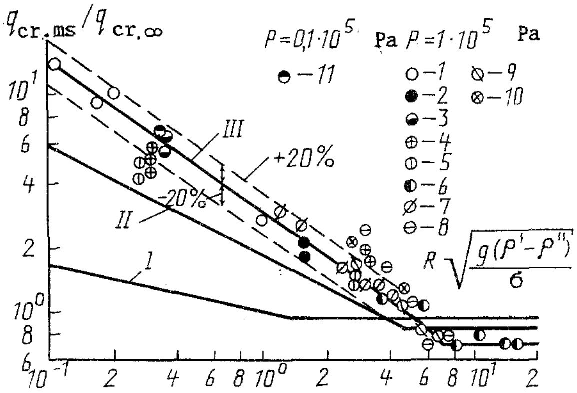

Fig. 2. Generalization of data on $q_{cr.ms}$: 1, 11) water; 2) ethyl alcohol; 3) PFP; 4) MD-3F; 5) DEF; 6) nitrogen [10]; 7) water [8]; 8) isopropyl alcohol [9]; 9) methyl alcohol [9]; 10) ethyl alcohol [9]; lines: I) horizontal cylinders [5]; II) spheres [5]; III) horizontal microsurfaces – from Eq. (7).

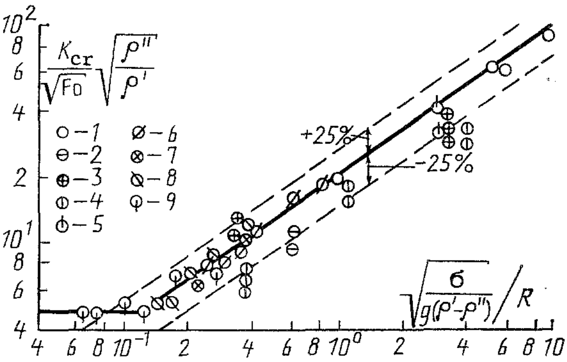

Fig. 3. Generalization of data on $q_{cr.ms}$ with Eq. (8): 1) water; 2) ethyl alcohol; 3) MD-3F; 4) DEF; 5) PFP; 6) water [8]; 7) ethyl alcohol [9]; 8) methyl alcohol [9]; 9) nitrogen [10].

of liquid from the bulk to the vaporization centers on the MS itself. This in turn leads to an increase in the temperature of the MS and the creation of additional vaporization centers at the periphery. These centers ultimately shut off the horizontal flow of liquid to the MS, and a vapor film forms on the latter.

Proceeding on the basis of these factors and the premises advanced in [11], we can conclude that the nucleate boiling crisis on the MS will be subject to the following law:

$$K_{cr} = C\,\mathrm{Fo}^{0.5}(\rho'/\rho'')^{0.5}(l_c/R_{ms})^m, \tag{8}$$

where $K_{cr} = q_{cr.ms}/r\rho''d_0f$; $\mathrm{Fo} = a/d_0^2f$; d_0 is the separation diameter of a vapor bubble; f is the frequency of separation of vapor bubbles; a is diffusivity.

It is evident from an analysis of Eq. (8) that the separation diameter of a vapor bubble has no effect on $q_{cr.ms}$, while the frequency of separation has an exponential effect. Here, the value of the exponent is 0.5. Using the recommendations in [11] in determining the separation frequency, we obtain a relation which generalizes both our experimental data and that from [8-10]:

$$K_{cr} = 20\sqrt{\mathrm{Fo}\,\rho'/\rho''}\,(l_c/R_{ms})^{0.65}. \tag{9}$$

Thus, with an accuracy sufficient for practical purposes, we can use Eqs. (7) and (9) to calculate $q_{cr.ms}$ for the boiling of liquids on small horizontal surfaces (see Figs. 2 and 3).

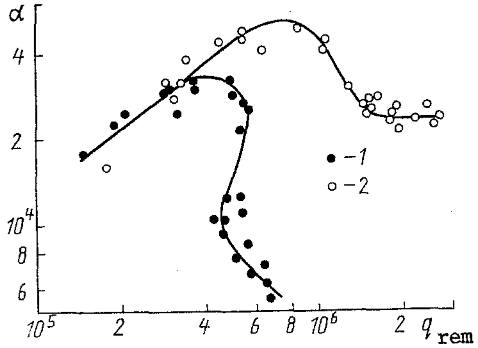

Fig. 4. Boiling curves of organofluorine liquid DEF on a microsurface 0.87 mm in diameter, mm: 1) MS without coating; 2) MS coated with one layer of a capillary-porous structure. α, W/(m²·K); q_{rem}, W/m².

A criterion which can be used to determine whether or not a surface can be classified as an MS is the simplex R/l_c. At $R < 8l_c$, the surface is an MS and the value of $q_{cr.ms}$ for it can be calculated from (7) or (9). For water, such surfaces are those with a radius less than 20 mm. For ethanol and organofluorine liquids, the surface must have a radius of less than 12 and 6 mm, respectively, to be considered an MS.

An increase in $q_{cr.ms}$ is possible with the application of a capillary-porous coating on the MS.

We saw $q_{cr.ms}$ approximately double with the application of a single layer of a copper-bearing metal-fiber coating 0.04 mm thick on an MS 0.87 mm in diameter in the case of the boiling of liquid DES (Fig. 4). Here, the porosity of the coating was 87%. The application of a capillary-porous coating also promotes more intensive heat transfer in the film boiling regime.

The higher values of $q_{cr.ms}$ and α obtained with the coated MS can be attributed to the fact that the capillary-porous structure has a framework with a high thermal conductivity. The framework of the structure transmits heat from the MS to the liquid. Additional vaporization centers are created, with the MS behaving as though it were broken down into individual cells. This makes it impossible for local vapor films to join together when the conditions prevailing at high values of q_{rem} impede heat transfer.

Thus, the completed study showed that the critical heat fluxes on microsurfaces are considerably higher than on an extended surface and can be determined by means of Eqs. (7) and (9).

The application of a capillary-porous structure to a microsurface nearly doubles the values of $q_{cr.ms}$.

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