HEAT-TRANSFER CRISIS IN LOW-TEMPERATURE EVAPORATIVE THERMOSIPHONS

G. A. Savchenkov and V. G. Kunakov

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An experimental investigation is performed for the heat-transfer crisis in open and closed low-temperature thermosiphons.

Evaporative thermosiphons (ET) are presently being applied in different branches of refrigeration and power engineering [1-4]. Questions of the optimal design of systems with thermosiphons are determined primarily by the constraints on the limit characteristics of the heat transfer at the heated section of the ET. There are neither reliable information nor recommendations on the analysis of conditions for the onset of the heat-transfer crisis in an open ET with lateral heating and cooling in the known domestic or foreign literature.

We shall understand the heat-transfer crisis of an evaporative thermosiphon to be a disturbance in the heat-transferring capability of the ET which is a result of crisis phenomena in the operation of the heated section under conditions of combined progress of the processes (hydrodynamic and thermal) in the whole ET cavity. In contrast to heat pipes with capillary structure, in which the hydrodynamic blockage conditions can be substantial, conditions resulting in local and total scalding of the heating surface are the main reason for a crisis in the ET. Depending on the boundary conditions on the heating section, the crisis is manifested differently. For q = const, an asymptotic rise in the wall temperature is observed on the heating section with a simultaneous diminution in the value of the transferable power (Fig. 1). Analogous results are obtained in [5]. The forms for the appearance of a crisis can be distinct and depend primarily on the degree of fullness by the intermediate heat carrier Ω, which governs the ratio between the volume of the liquid phase of the heat carrier under normal conditions and the physical volume of the thermosiphon. For $\Omega \leq 1.5\%$ a film heat-transfer mechanism is realized in the ET [8-10], and according to visual observations, the crisis is a result of local desiccation of the liquid film, resulting in burnout of the housing [10]. For $\Omega \geq 30\%$ the fluid phase with low compressibility coefficients predominates in the thermosiphon cavity, and in a number of cases this specifies an explosion of the apparatus as $q \to q_{max}$, which is associated with an abrupt rise in pressure [5].

Under heating conditions close to t = const, disturbance of the main functions of the apparatus (the transfer of heat flux) is characteristic rather than a temperature rise as $q \to q_{max}$. In this case it is expedient to record the onset of the crisis by the outgoing power rather than by the wall heating temperature. It is difficult to determine the temperature jump since it occurs at the site of "dry spot" formation, whose appearance is equally probable at different surface sites and is sporadic in nature [11].

For $\Omega \leq 1.5\%$ the theoretical analysis of the crisis is performed in the form of an inverted Nusselt problem [10]. Up to now the physical reason for the crisis has not been clarified for $3\% \leq \Omega \leq 60\%$. Papers [5-7, 10], whose results cannot be compared, are devoted to the question under consideration. Thus, crisis phenomena in thermosiphons with endface heat supply and outgo were studied for the degrees of fullness $10\% \leq \Omega \leq 80\%$

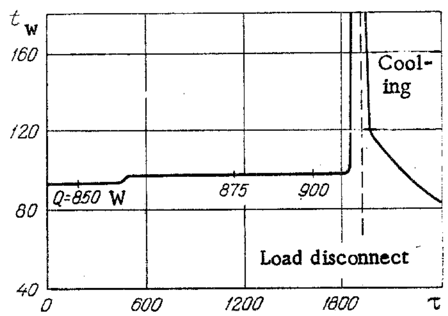

Fig. 1. Diagram of the change in wall temperature on the heating section (at the site of the "dry spot") upon onset of the heat-transfer crisis of an evaporative thermosiphon.

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TABLE 1. Conditions for Conducting the Experiment

<table>
<tr><td colspan="5">Open thermosiphons</td><td colspan="11">Closed thermosiphons</td></tr>
<tr><td colspan="5">C_2H_5OH</td><td rowspan="2">main param- eters</td><td rowspan="2">type of heat carrier</td><td rowspan="2">$\frac{d}{l_0}$</td><td rowspan="2">impurity content ψ, %</td><td>$\varphi=90°$</td><td colspan="6">$\varphi=90°, 80°, 65°, 45°, 14°, 4°$</td></tr>
<tr><td rowspan="10">$l_\Sigma=500$ mm, $l_0=100$ mm, $\Omega=18–20\%$, $\varphi=90°$</td><td>l_i, mm</td><td>$d=$ 5 mm</td><td>$d=$ 9 mm</td><td>$d=$ 14 mm</td><td>$\Omega=$ 1,32%</td><td>$\Omega=$ 2,9%</td><td>$\Omega=$ 10,5%</td><td>$\Omega=$ 26,5%</td><td>$\Omega=35\%$</td><td>$\Omega=50\%$</td><td>$\Omega=60\%$</td></tr>
<tr><td>100</td><td>1</td><td>2</td><td>3</td><td rowspan="4">$l_\Sigma=500$
$l_i=150$
$d=22$</td><td rowspan="2">DES</td><td rowspan="4"></td><td>3–8,6</td><td>1'</td><td>2'</td><td>3'</td><td>4'</td><td>5'</td><td>6'</td><td>7'</td></tr>
<tr><td>150</td><td>4</td><td>5</td><td>6</td><td>100</td><td>—</td><td>8'</td><td>9'</td><td>10'</td><td>11'</td><td>12'</td><td>13'</td></tr>
<tr><td>165</td><td>—</td><td>7</td><td>—</td><td>F-113</td><td>0,58–3,24</td><td>14'</td><td>15'</td><td>16'</td><td>—</td><td>—</td><td>—</td><td>—</td></tr>
<tr><td>200</td><td>8</td><td>—</td><td>9</td><td>C_2H_5OH</td><td>1,04–3,5</td><td>17'</td><td>—</td><td>—</td><td>—</td><td>—</td><td>—</td><td>—</td></tr>
<tr><td rowspan="2">230</td><td rowspan="2">—</td><td rowspan="2">10</td><td rowspan="2">11</td><td rowspan="5">$l_\Sigma=500$
$l_i=150$
$d=10$</td><td rowspan="5">C_2H_5OH</td><td rowspan="2"></td><td rowspan="5"></td><td colspan="2">$\Omega=3\%$</td><td colspan="2">$\Omega=10\%$</td><td colspan="2">$\Omega=30\%$</td><td>$\Omega=50\%$</td></tr>
<tr><td colspan="7">$\varphi=90°$</td></tr>
<tr><td rowspan="3">250</td><td rowspan="3">12</td><td rowspan="3">13</td><td rowspan="3">14</td><td>0,1</td><td colspan="2">18'</td><td colspan="2">19'</td><td colspan="2">20'</td><td>21'</td></tr>
<tr><td>0,041</td><td colspan="2">22'</td><td colspan="2">23'</td><td colspan="2">24'</td><td>25'</td></tr>
<tr><td>0,032</td><td colspan="2">—</td><td colspan="2">—</td><td colspan="2">26'</td><td>—</td></tr>
</table>

in [5]; the crisis in ET with lateral heat supply and outgo was studied in [10] in the film heat-transfer mode; and the investigation was performed only in open thermosiphons in [6, 7].

Since the crisis is accompanied by a diminution in the transferable heat in time, then the test data are customarily generalized by the results of measurement in the stationary state preceding the onset of the crisis, i.e., $q_{max} = Q_{max}/\pi d l_h$.

The experimental apparatus on which the researches were performed is described in [12]. The heat-transfer crisis was studied in open and closed ET. Conditions close to t ≈ const were simulated in the heating section by the method of a thick-walled cylinder [13] fabricated from copy M2. The condition q = const was realized by using a Nichrome electrical heater. The influence of geometric factors, degrees of fullness, thermophysical properties of the heat carrier, orientations in space, noncondensing admixtures (air), and boundary conditions on the heating section on the crisis onset condition was studied. The conditions for conducting the tests are represented in Table 1.

The open thermosiphons in [6, 7] had a cooling section coupled to an infinite volume of liquid of one kind. In this paper the ET are coupled to the environment through a 2-mm-diameter endface hole which permitted maintenance of a constant saturation temperature during the experiment. The magnitude of this temperature was checked by a special thermocouple probe. The probability of entrainment of the intermediate heat carrier in the environment was determined by checking measurements on the quantity of fluid before and after conducting the experiment. Heat-carrier entrainment is not observed in 7-h continuous operation of the ET for $\Omega \leq 30\%$. Measurement of the intermediate heat-carrier temperature in open thermosiphons was performed by thermocouples whose method of fastening is described in [12].

The relation between the state of intermediate heat-carrier saturation at the time of crisis and the degree of fullness was determined experimentally in [5]. The stable nature of such a relation, independent of the cooling conditions and determined only by the thermophysical properties of the substance and the degree of fullness, is of known interest for engineering computations. The small amount of experimental material (9 points in all) made it necessary to verify the results obtained in [5]. A comparison performed permitted the conclusion that the derivations of [5] are particular in nature and cannot be extended to the case of ET with lateral heat supply and outgo. In contrast to [5], where the crisis for Ω = 20–30% corresponds to the critical state of the intermediate heat carrier, disturbance of the heat transfer set in earlier for lateral heating (Fig. 2). The hypothesis proposed in [5] about the thermodynamic nature of the crisis cannot explain the fact of the influence of the ET diameter and the method of delivering the heat flux on the value of the critical load (Fig. 2). Moreover, the qualitative agreement between the data obtained from [5] should be noted in that the maximum

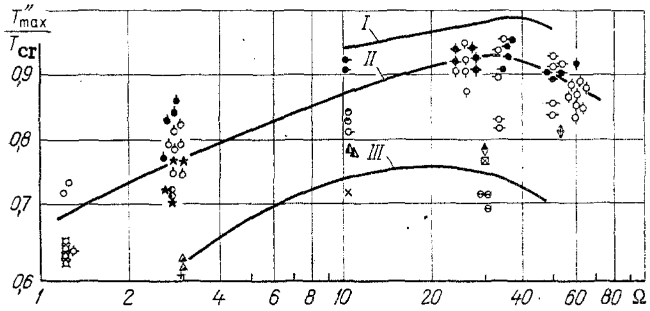

Fig. 2. Comparison between results of testing closed evaporative thermosiphons and the data in [5]: I) data from [5]; II, III) authors' results; II) thermosiphon diameter 22 mm; III) 10 mm (notation for the points is presented in Fig. 3 and Table 1).

transferable heat fluxes are observed for Ω = 20-30% (the so-called "optimal" degree of fullness).

An analysis of the results obtained permits the conclusion that the influence of the heat delivery method (endface or lateral) and the constriction (diameter) on the heat-transfer crisis can be explained by conditions for vapor-phase formation on the heating section, i.e., from the aspect of the hydrodynamic theory of crises.

The most complete experimental study of the crisis in open ET was performed in [6, 7]. The influence of the lengths of the heating sections (200, 300, and 1000 mm), the diameters (10.7 and 28.4 mm), the heat-carrier properties (water distillation, ethyl alcohol, normal hexane, carbon tetrachloride), the heating conditions (q = const, t = const), and the underheating of the intermediate heat carrier to saturation (Δt_{sub} = 2-54°C) on the condition for the heat-transfer crisis was studied. The crisis was investigated in the annular gap on the heated section (δ = 1.6, 4.7, 8.2 mm). To do this, a displacer (rod) was placed within the element. The results obtained are extended in criterial form and agree satisfactorily with the data [14, 15] (Fig. 3). The selection of the criteria in [1] is done within the framework of dimensional analysis and on the basis of conceptions about the hydrodynamic nature of the process. The results of visual observations are the foundation for such an approach. Definite agreement between these results is established in a comparison of the intrinsic and

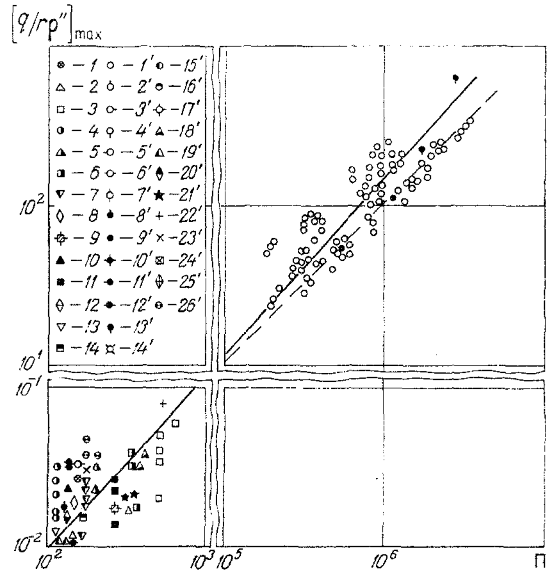

Fig. 3. Comparison between test results for open evaporative thermosiphons and the data in [6, 7, 14, 15]: 1') data from [6, 7]; 9') [14]; 13') [15]; solid lines are the data from (1) and the dashed are the authors' results. The values of our results are presented in Table 1. $\Pi = (\sigma/\mu'')(\rho'\mu'/\rho''\mu'')(S/F_h)[1.0 + 5.0(\rho'/\rho'')^{0.8}(S/F_h)(C_p'\Delta t_{sub}/r)]$.

literature data [6, 7, 14, 15] on the investigation of the heat-transfer crisis in open and closed ET. The corrected dependence [6, 7] (Fig. 3)

$$\left[\frac{q_h}{r\rho''}\right]_{\max} = 7.254\cdot10^{-5}\left\{\frac{\sigma}{\mu''}\left(\frac{\rho'\mu'}{\rho''\mu''}\right)^{0.2}\frac{S}{F_h}\left[1+5.0\left(\frac{\rho'}{\rho''}\right)^{0.8}\frac{S}{F_h}\frac{C'_p\Delta t_{sub}}{r}\right]\right\}^{1.07} \tag{1}$$

can be used with the maximum error of 100%.

Since the investigations in [6, 7, 14, 15] were conducted with underheating, the critical heat fluxes exceed the results obtained in this paper under saturation conditions.

The investigations performed showed that the limiting reduced rate of vapor formation $w'' = [q_h/r\rho'']_{max}$ is related to the boiling crisis, but cannot be projected as the governing characteristic of a crisis since the function $w'' = f(q_h)$ has an extremum and the crisis can set in at a different point of the curve depending on the species of heat carrier, the geometric characteristics, etc. This can explain the significant spread in the test data in Fig. 3.

The hydrodynamic theory of the nucleate boiling crisis in an unbounded volume assumes the self-similar nature of the crisis relative to the size of the heater under free convection conditions [16]: for $R > \sqrt{\sigma/g(\rho' - \rho'')}$ for horizontal cylinders, and for $R > 0.25\sqrt{\sigma/g(\rho' - \rho'')}$ for vertical cylinders.

The influence of the surface size on the critical heat flux was examined in [17, 18]. A significant increase (two- to five-fold) in the critical heat flux is detected experimentally in a number of papers for a diminution in the radii of horizontal cylinders (wires) and spheres as compared with the critical heat flux during boiling on plane surfaces ($q_{max\,\infty}$). A hypothesis was expressed in [17] about the mutual relation between the separated diameter of the bubble (D_0) and the critical heat flux (q_{max}) in the form

$$\frac{q_{max}}{q_{max\,\infty}} = \left(\frac{D_\infty}{D_0}\right)^2, \tag{2}$$

$$D_\infty = 2\sin\theta\sqrt{\frac{3}{2}\,\frac{\sigma}{g(\rho'-\rho'')}}, \tag{3}$$

where D_∞ is the separated bubble diameter during boiling on a plane surface in a large volume.

An estimate of the influence of the positive curvature (boiling on a convex surface) on the separated diameter of a vapor bubble is presented in [17, 18] on the basis of the balance equation for the surface tension forces and the lift forces acting on a bubble

$$D_0^+ = D_\infty\sqrt{\frac{2R}{2R+D_\infty}}\left[\frac{2R+D_\infty}{4R} + 0.273\sqrt{\frac{2R+D_\infty}{R}} + 0.277\right]^{1/3}, \tag{4}$$

where R is the radius of a curvilinear surface. It is easy to see that $D_0^+ \leq D_\infty$, and therefore

$$q^+_{max}/q_{max} \geqslant 1.0. \tag{5}$$

By using the approach of [17, 18], the following equation for the separated bubble diameter, formed within the pipe (thermosiphon):

$$D_0^- = \sin\left[\theta + \operatorname{arcctg}\frac{\frac{2R}{D_0} - \cos\theta}{\sin\theta}\right]\sqrt{\frac{3}{2}\,\frac{\sigma}{g(\rho'-\rho'')}}. \tag{6}$$

can be obtained for a qualitative estimate of the influence of negative curvature (a concave surface) on the boiling crisis. Hence, $D_0^- \geq D_\infty$ and therefore

$$q^-_{max}/q_{max\,\infty} \leqslant 1.0. \tag{7}$$

Equations (4) and (6) satisfy the condition for passage to the limit as $R \to \infty$ and take the form of the equation for the separated vapor bubble diameter on a flat surface (D_∞). However, (6) can be used only for a qualitative analysis since the bubble formation mechanism under constrained conditions is distinguished by great complexity. It was noted in [19] that the "closeness effect" is that for a small system volume or for a high frequency of nucleus formation the appearance of bubbles changes the state of the medium, which is very complicated to take into account. Hydrostatic pressure forces, which tend to squeeze the bubbles to the surface, also exert influence on the condition of bubble formation within the pipe, which can also increase the separated diameter [20].

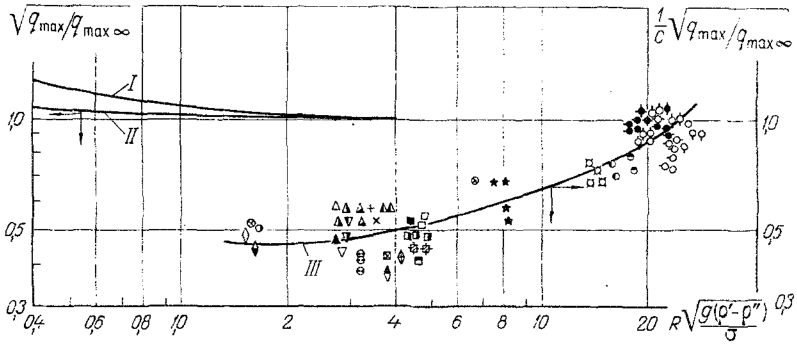

Fig. 4. Extension of test data on the heat-transfer crisis of closed and open thermosiphons within the framework of the hydrodynamic theory of crises, taking account of the influence of surface curvature: I, II) data for boiling on a convex surface; I) corresponds to Eq. (2); II) to (8); III) authors' data extended by dependence (9) (values of the points are presented in Table 1).

Equation (2) agrees qualitatively with the experimental data [17, 18] but does not yield satisfactory quantitative agreement because of the assumptions made in the derivation. Consequently, the test data in [17, 18] are extended by an empirical dependence whose functional relationship is determined from an analysis of (2)-(4) (Fig. 4):

$$\frac{q^{+}_{max}}{q_{max\,\infty}} = 1 + 2.55 \exp\left(-3.44 \sqrt{R \sqrt{\frac{g(\rho'-\rho'')}{\sigma}}}\right) = f\left(R \sqrt{\frac{g(\rho'-\rho'')}{\sigma}}\right). \tag{8}$$

The results of extending the test data on the heat-transfer crisis in ET, obtained in this paper, are represented in Fig. 4. The data agree with (7) and are extended with a maximum error of 20% by the empirical dependence

$$\frac{q^{-}_{max}}{q_{max}} = C^2\left[0.4 + 0.024\, R \sqrt{\frac{g(\rho'-\rho'')}{\sigma}}\right]^2, \tag{9}$$

$$q_{max\,\infty} = 0.14\, r \sqrt{\rho''}\, \sqrt[4]{g(\rho'-\rho'')}, \tag{10}$$

where $C = A(d/l_0)^{-0.44}(d/l_i)^{0.55}\Omega^n$; for $\Omega \le 35\%$, A = 0.538 and n = 0.13, while for $\Omega \ge 35\%$, A = 3.54 and n = −0.37. The domain of application of dependence (9) is bounded by the condition

$$1.0 \leqslant R \sqrt{\frac{g(\rho'-\rho'')}{\sigma}} \leqslant 30. \tag{11}$$

Dependence (9) obtained is more reliable than (1), extends the test data (see Table 1) on the heat-transfer crisis in closed and open ET in a broad range of changes in the degree of fullness by the intermediate heat carrier ($2.9\% \le \Omega \le 60\%$), the geometric characteristics (d = 5-22 mm; d/l_0 = 0.0161-0.22; d/l_i = 0.04-0.22), the orientation in space (φ = 90-4°), the thermophysical properties of the heat carrier, and for the boundary conditions t ≈ const and q = const on the heating section.

According to (9), the complex taking account of the influence of the slope ($\sin\varphi$) has practically no influence on the value of the maximum specific heat flux. As a recommendation for the design of systems with ET it can be mentioned that an insignificant extremum of the dependence $q^{-}_{max} = f(\sin\varphi)$ arrives at a slope of φ = 45-65°.

NOTATION

q, specific heat flux; Q, heat flux; Ω, degree of heat carrier fullness; d, thermosiphon diameter; l, length; S, thermosiphon cross section; F, heating surface area; R, thermosiphon (cylinder) radius; D, bubble diameter; δ, size of the annular gap; r, latent heat of vapor formation; ρ, density; σ, surface tension; μ, dynamic viscosity; C_p, specific heat; t, temperature; w, velocity; g, free-fall acceleration; A, a coefficient; φ, slope; θ, wetting angle. The subscripts are: 0, cooling; max, greatest; h, heating; ″, vapor phase; ′, liquid phase; sub, underheating the fluid to the state of saturation; ∞, boiling in an infinite volume, +, a convex, and −, a concave surface.

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