along the HP length becomes less substantial. Thus, for $\xi(z) = 0.3$ and $\bar{z} = 0.9L_e$ the mean velocity of fluid motion in the evaporator is 1 m/sec. Analysis of the results obtained permits making a deduction about the necessity of taking account of the inertial motion component only in the evaporation zone of the HP, where heat-carrier acceleration and deceleration phases exist.

## NOTATION

$r, \theta, z$, coordinates in a cylindrical coordinate system; $\varphi$, capillary half-angle; $r_w$, magnitude of the capillary wall wetted by the fluid; $r_s$, radius of the fluid meniscus; $r_{w0}$, height of the capillary wall; $S_0$, capillar half-width; L, length of the heat pipe zone; R, radius of curvature of the fluid meniscus; F, capillary through section; $\psi(z)$, fluid contact angle with the wall material; $\alpha$, wetting angle; $W_0$, axial velocity scale factor; W, axial velocity of heat carrier motion; $\gamma$, HP slope; V, evaporation or condensation rate; $\xi(z)$, a dimensionless function of the fluid meniscus deepening; $\rho$, density; g, free-fall acceleration; $\sigma$, surface tension coefficient; $\mu$, dynamic viscosity; q, heat flux density; Fr, Re, We, Froude, Reynolds, and Weber numbers. Subscripts: e, evaporator; a, adiabatic zone, c, condenser; v, vapor; L, fluid; max, maximal.

## LITERATURE CITED

1. P. S. Ayyaswamy, I. Catton, and D. K. Edwards, "Capillary flow in triangular grooves," ASME, 41, 332-336 (1974).
2. L. L. Vasil'ev, A. N. Abramenko, and L. E. Kanonchik, "Heat transfer during fluid evaporation and boiling in evaporator grooves," Inzh.-Fiz. Zh., 39, No. 3, 449-457 (1980).
3. L. L. Vasil'ev, A. N. Abramenko, and L. E. Kanonchik, "Heat transfer during fluid evaporation and boiling in evaporator grooves," Inzh.-Fiz. Zh., 39, No. 5, 826-832 (1980).
4. V. A. Krivonos, "Fluid flow in triangular grooves under the effect of capillary forces," Heat Transfer in Cryogenic Apparatus [in Russian], Inst. Heat and Mass Transfer, BSSR Acad. Sci., Minsk (1979), pp. 30-49.

# CRISIS PHENOMENA UPON EVAPORATION IN GRID CAPILLARY AND POROUS COATINGS AND ARTERIAL STRUCTURES OF HEAT PIPES

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The article presents the results of experimental investigations of critical (limit) heat fluxes upon evaporation on porous coatings, and it substantiates the physical model of the process.

When the density of heat fluxes in porous structures is high, processes of evaporation may be accompanied by abrupt infringements of the conditions of heat transfer, leading to a sudden and substantial increase of the wall temperature. Such phenomena are called crisis phenomena.

According to the conditions of heat liberation and supply of heat carrier, the following situations may be distinguished.

1. Heat is conducted from the wall to the wetted structure: a) with capillary supply of the heat carrier, b) by inundation, c) with combined supply.

2. Heat is conducted from the skeleton to the heat carrier (internal heat liberation): a) under conditions of capillary supply; b) by inundation; c) with supply of liquid under the effect of pressure forces.

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TABLE 1. Experimental Conditions

| Heat carrier | Water | Ethanol | Freon-113 |
| --- | --- | --- | --- |
| Pressure $p_s$, MPa | 0,005—0,1 | 0,003—0,1 | 0,1 |
| Grid structures (material) | Size of cell $a$, μm | | |
| 1. 1Kh18N9T | 40, 60, 125, 200, 450, 1600 | 40, 60, 125, 200, 450 | 40, 60, 125, 200 |
| 2. Brass | 80, 160 | 80, 160 | 160 |
| 3. Copper | 45 | 45 | 45 |
| No. of layers n, pcs. | 1—24 | 1—9 | 1—9 |
| Level of heat carrier (± H, mm) | | −140—0—+50 | |
| Limit heat fluxes $q_m \cdot 10^{-4}$, W/m² | 1—100 | 1—50 | 0,3—25 |

3. Heat is conducted from the vapor–gas space to the evaporation surface, i.e., the phase boundary: a) with supply of liquid under the effect of pressure forces; b) with capillary supply.

This classification cannot claim to be exhaustive, but it comprises most of the known variants of evaporation in porous structures. We note that for each characteristic combination of conditions of heat supply and trickle feeding of the liquid there are possible its own features of crisis phenomena.

The present article deals only with crisis phenomena for one combination of conditions of heat supply and trickle feeding (case 1a) on the basis of experimental investigations of critical (limit) heat fluxes $q_m$ in capillary grid structures of heat pipes.

The experimental investigations were carried out with uniform and nonuniform grid structures on a test bench and by a method that were both described in [1]. The main unit of the experimental installation is a copper block, i.e., a heat concentrator whose end face with 30 mm diameter formed the experimental heating surface. With the aid of a gripping device specimens of capillary porous grid structures were attached to the heating surface. The number of layers and the material of the grids, the kind of heat carrier and the saturation pressure were being varied. The conditions and range of experimental investigations are presented in Table 1.

The experimental installation made it possible to carry out experiments at a heat-flux density of up to $q = 10^6$ W/m². Most of the results were obtained for structures attached to the heating surface, and some data were obtained for structures that were specially forced away from the wall with the aid of calibrated packing pieces.

The limit heat fluxes were ascertained in the following manner. In the first case, upon interruption of heat transfer, the temperature field became equalized along the axis of the thermal wedge. The heat flux corresponding to an abrupt increase of the thermal emf of the thermocouples mounted in the block near the heating surface was regarded as the limit flux.

In other cases, e.g., in experiments with fine capillary porous structures (number of layers n = 1, 2), the fluxes at which drainage of the cells in the central part of the heating surface occurred were regarded as limit fluxes. Spillover of heat along the massive copper wall from dried sections to places of intense heat removal was able to delay the rise of the temperature (crisis by drying).

In certain structures we found that after a certain level of thermal load had been attained, the temperature slowly rose (by up to 15°K/h), which was also identified with the onset of a crisis phenomenon (the so-called "extended crisis").

The limit heat fluxes were ascertained experimentally by successive approximation: at first the power was increased in large steps; after the probable range of crisis had been established and the surface had been cooled up to complete cessation of boiling, the experiment was repeated with continuous smooth increase of the thermal load.

The increase of temperature in the thermal wedge was ascertained by a special thermocouple mounted at the heating surface. The reproducibility of the values of $q_m$ was checked by repeating the experiments.

Experimentally obtained typical partial results are presented in Fig. 1. Figure 1a illustrates the dependence of $q_m$ on the number of layers of the grids in the structure n. It can

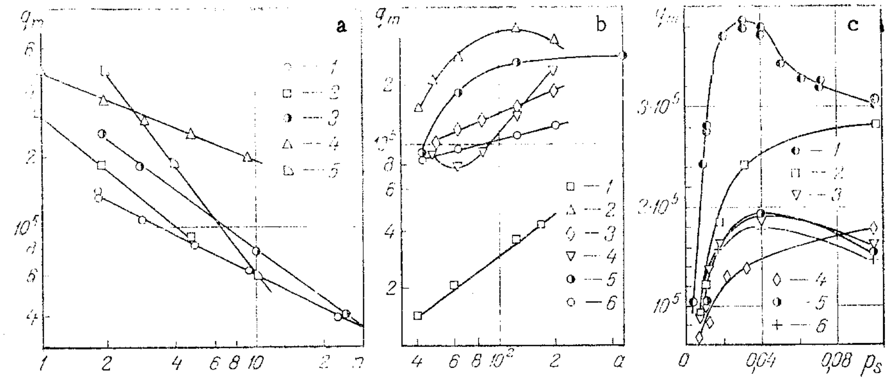

Fig. 1. Characteristic empirical regularities of the limit heat fluxes $q_m$ in evaporation on porous grid coatings. a) Water, $p_s$ = 0.1 MPa: 1) stainless steel, $a$ = 60 μm (capillary trickle feeding); 2) copper, $a$ = 45 μm; 3) stainless steel, $a$ = 60 μm (inundation); 4) stainless steel, $a$ = 200 μm; 5) stainless steel, $a$ = 125 μm; b) $p_s$ = 0.1 MPa, Freon-113: 1) n = 2; water: 2) n = 2; 3) 3; 4) 5; ethanol: 5) n = 2; 6) 3; c) ethanol, stainless steel: 1) n = 2 $a$ = 450 μm; 2) n = 2, $a$ = 125 μm; 3) n = 1, $a$ = 60 μm; 4) n = 2, $a$ = 60 μm; 5) brass, n = 2, $a$ = 160 μm; 6) stainless steel, nonuniform structure: 1 layer 60 μm + 2 layers 200 μm.

be seen that when the number of layers of the grids increases, the limit density of the heat flux decreases. Figure 1b shows the dependence of $q_m$ on the size of the cell $a$. The nonmonotonic nature of this dependence may be due to the joint effect of the cell size $a$ and the thickness of the layer of the grid $\delta_{la}$ on the magnitude of $q_m$: $a$ and $\delta_{la}$ are mutually correlated by certain standard dimensions: as a rule, a greater thickness of the grid corresponds to a larger cell.

With increasing thickness of the coating, the resistance to the escape of vapor increases whereas an increase of the size of the cell leads to a decrease of the capillary potential. The interaction of these two factors determines the shape of the curve $q_m = f(a)$. By the term capillary potential the authors mean a quantitative characteristic of the ability of a capillary structure to supply to and maintain a liquid in the near-wall zone. In most cases the capillary potential is determined by the magnitude const $\sigma/L$, where L is the characteristic dimension determining the mean radius of curvature of the phase boundary in the zone of evaporation.

The effect of the saturation pressure $p_s$ on the magnitude of $q_m$ (Fig. 1c) is also ambiguous. In the range of reduced pressures both a decrease and some increase of $q_m$ were noted, and $q_m$ attained its maximum in the range $p_s$ = 0.03 MPa. The last case is characteristic of fine and nonuniform capillary porous structures presented below, which are marked by low hydraulic resistance to the escape of vapor.

A number of experiments were carried out with nonuniform capillary structures composed of grids with different cell sizes $a$ across the thickness, but in such a way that the layer with the smallest $a$ was next to the heating surface. Experimental investigations with nonuniform coatings showed, on the whole, a larger $q_m$ than uniform coatings. A small size of $a$ in the near-wall zone determines the high capillary potential, and a large size of the higher layers facilitates the escape of the vapor phase from the nonuniform structure.

Experiments were also carried out with modeling of the processes in the zones of evaporation and transport on models of flat heat pipes with arterial structures. The arteries were made of two layers of grids with $a$ = 60 μm or of one layer with $a$ = 130 μm by rectangular corrugation with a pitch of 3.5 mm and height of profile 1.5 mm. The results in regard to $q_m$ for nonuniform structures and modeling experiments on arterial structures are presented in Table 2.

In special experiments the size of the gap between the heating surface and the capillary grid structure was changed. An increase of the gap greatly reduced the value of the limit heat flux $q_m$.

TABLE 2. Results in Regard to $q_m$ for Nonuniform and Arterial Structures

| Serial No. | Structure | $p_s$, MPa | $q_m \cdot 10^{-4}$, W/m² | $l_{tr}$, $10^3$, m |
|---|---|---|---|---|
| 1 | 1 layer 40 μm + 2 layers 130 μm | 0,1 | 23,3 | 55 |
| 2 | 1 layer 40 μm + 3 layers 130 μm | 0,1 | 14,4 | 55 |
| 3 | 1 layer 45 μm + 2 layers 200 μm | 0,1 | 19,8 | 55 |
| 4 | 1 layer 60 μm + 2 layers 200 μm | 0,01; 0,03; 0,1 | 15,0; 19,9; 16,5 | 55 |
| 5 | 1 layer 60 μm + 1 layer 200 μm + 1 layer 130 μm | 0,01; 0,03; 0,1 | 16,5; 19,8; 17,0 | 55 |
| 6 | 2 layers 40 μm + artery | 0,02; 0,05; 0,1 | 41,3; 55,4; 72,7 | 165 |
| 7 | The same | 0,1 | 23,6 | 205 |
| 8 | 2 layers 40 μm + 1 layer 130 μm + artery | 0,004; 0,02; 0,05; 0,1 | 36,0; 50,0; 48,0; 64,4 | 59 |
| 9 | 1 layer 60 μm + 1 layer 130 μm + artery | 0,1 | 64,0 | 59 |
| 10 | 7 layers 60 μm + 1 layer 130 μm + artery | 0,02; 0,03; 0,045; 0,1 | 44,0; 46,4; 50,7; 60,0 | 154 |

The obtained results, known data [2-5], and visual observations served as the basis of the following physical notions concerning the mechanism of crisis phenomena upon evaporation in capillary grid structures under conditions of capillary trickle feeding, in particular: drying of the heating surface with a capillary porous coating, accompanied by abrupt reduction of heat transfer, is a consequence of the fact that buoyancy developed by the capillary and other forces (e.g., the force of gravity) does not suffice for ensuring transport of the liquid. Such a phenomenon in "pure" form is put into effect in heat pipes operating in evaporation regime, and it is characterized by gradual deviation from trickle feeding the heat carrier to individual sections of the zone of evaporation of the heat pipe in proportion to the increase of the thermal load. This is the phenomenon of the so-called hydrodynamic limit of heat pipe operation when the magnitude of the capillary potential is smaller than the hydrodynamic resistance of liquid transport in regard to the structure and static pressure due to the level gradient of the liquid

$$\frac{4\sigma}{a} \leqslant \frac{\mu' w' l}{k_p} + \rho' g h \sin\beta. \tag{1}$$

If we proceed from the hydrodynamic model of the crisis of heat transfer [6], we must take into account the losses of mechanical energy in filtration of a biphase flow at the heating surface [7, 8]. Taking these losses into account according to [7] provides the condition of infringement of the stability of the biphase boundary layer due to the effect of "constraint":

$$E \geqslant k_1^2 \Pi - k_2 \Pi_f, \tag{2}$$

where E is the kinetic energy of the nominally injected vapor stream in boiling; $\Pi$, potential energy of the stably existing vapor film; $\Pi_f$, work on overcoming the frictional forces through the elements of constraint.

When evaporation occurs in capillary porous coatings, a curved phase boundary forms in the cells near the heating surface under the effect of capillary forces, and this phase boundary may be regarded as a source of capillary potential. The process of nucleate boiling on capillary porous coatings is accompanied by the ejection of liquid drops entrained by the vapor flow, and this entails additional expenditures of mechanical energy. With this taken into account, condition (2) may be represented as follows:

$$E \geqslant k_1^2 \Pi - k_2 \Pi_f + c_3 \Pi_\sigma - \Delta E_{en}. \tag{3}$$

Thus the energy-related treatment of the equation [6] of the crisis of nucleate boiling after [8] yields

$$\left(\frac{q_m}{r\rho''}\right)^2 \rho'' \geqslant k_1^2 (\rho' - \rho'') \sqrt{\frac{\sigma}{g(\rho' - \rho'')}}. \tag{4}$$

Consequently,

$$E = \left(\frac{q_m}{r\rho''}\right)^2 \rho'', \quad k_1^2\Pi = c_1 \left(\frac{q_m}{r\rho''}\right)^2 \rho''. \tag{5}$$

Putting $k_2\Pi_f \sim k_2\Delta p_f$, we will analyze the hydraulic resistance $\Delta p_f$, using the known assumptions of the hydraulics of biphase flows [9]. In the general case we may write

$$\Delta p_f = \Delta p_0 f(\varphi), \tag{6}$$

where $f(\varphi)$ is a function of the structure and of the true volumetric quantity of steam $\varphi$ of a biphase flow. If we put in the first approximation that with $q \to q_m$, $\varphi \to \varphi_m$, where $\varphi$ = idem for different conditions, we may replace $k_2\Delta p_f$ by $c_2\Delta p_0$, where $\Delta p_0$ is the hydraulic resistance of a stack of grids to single-phase flow.

Examining filtering of a single-phase flow (of vapor) under conditions of local resistance on the basis of [10], we obtain

$$\Delta p_0 \sim \xi \frac{\rho'' w_0^2}{2} \sim 1.7n(1-\varepsilon)\frac{2.3-\varepsilon}{\varepsilon}\left(\frac{q_m}{r\rho''}\right)^2 \rho'', \tag{7}$$

where $w_0 = q_m/r\rho''$.

The component of potential energy determined as the capillary potential in Eq. (3) may be written in the form

$$k_3\Pi_\sigma \sim c_3 \frac{\sigma}{a}. \tag{8}$$

The magitude of the entrainment of liquid can be evaluated from the balance of impulses:

$$\Delta p \sim g_{en} w. \tag{9}$$

We adopt the order of magnitude of w proceeding from the conditions of escape upon rupture of the vapor cavity:

$$w \sim \sqrt{2\Delta p/\rho''}. \tag{10}$$

Then the density of the entrained mass flow is

$$g_{en} \sim \sqrt{\Delta p \rho''/2}. \tag{11}$$

The kinetic energy of entrainment of the liquid can be evaluated as

$$\Delta E_{en} \sim g_{en} \frac{q_m}{r\rho''}. \tag{12}$$

Since the decisive contribution to the excess pressure gradient is made by the capillary forces,

$$\Delta p \sim \sigma/a. \tag{13}$$

Visual observations showed that entrainment of liquid is the smaller, the thicker the capillary porous structure is and the smaller the permeability is. Therefore, with a view to (11)-(13), we obtain

$$\Delta E_{en} \sim \frac{q_m}{r\rho''} \sqrt{\frac{\rho''\sigma}{a}} f(n, k_p). \tag{14}$$

Substitution of the terms of (4), (5), (7), and (14) into relation (3) and joint examination with (1) on condition that $w' = Q/(r\rho'\delta_{1a}P)$ $Q = q_m F$, yield the expression

$$\left(\frac{q_m}{r\rho''}\right)^2 \rho'' + \frac{q_m \nu' F l}{rPk_p n\delta_{1a}} + \frac{q_m}{r\rho''}\sqrt{\frac{\rho''\sigma}{a}} f(n, k_p) \geqslant c_1 \left(\frac{q_m}{r\rho''}\right)^2 \rho'' - $$
$$- c_2 1.7n(1-\varepsilon)\frac{2,3-\varepsilon}{\varepsilon}\left(\frac{q_m}{r\rho''}\right)^2 \rho'' + c_3\left(\frac{4\sigma}{a} - \rho' g h \sin\beta\right). \tag{15}$$

We represent the second and third terms in the first part of inequality (15) in the form

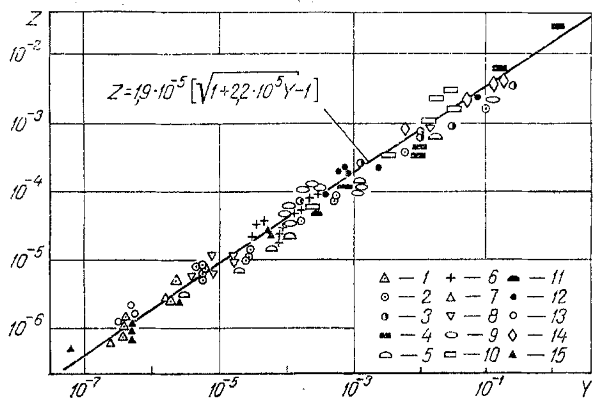


Fig. 2. Generalization of the experimental data according to relation (19). Water, stainless steel: 1) $a$ = 40 μm, n = 2,3; 2) $a$ = 60 μm, n = 2-10, 24; 3) $a$ = 125 μm, n = 2-10; 4) $a$ = 200 μm, n = 2-9; 5) brass, $a$ = 80 μm, n = 2-5; 6) data on modeling on arteries (Nos. 6-10, Table 2); ethanol, stainless steel: 7) $a$ = 40 μm, n = 2,3; 8) $a$ = 60 μm, n = 2,9; 9) $a$ = 125 μm, n = 2,8; 10) $a$ = 450 μm, n = 2,3; brass: 11) $a$ =80 μm, n = 3,9; 12) $a$ = 160 μm, n = 2,3; 13) copper, $a$ = 45 μm, n = 2; 14) nonuniform grid structures (Nos. 1-3, Table 2); 15) Nos. 4 and 5 in Table 2.

$$\frac{q_m}{r}\,\frac{\nu' Fl}{k_p n\delta_{1a}P}\left(1+\sqrt{\frac{\sigma}{a\rho''}}\,\frac{f(n,\,k_p)n\delta_{1a}P}{\nu' Fl}\right). \tag{16}$$

From the data of the experiments we may accept that $f(n, k_p)k_pn\delta_{1a} \approx$ const. For the given conditions $Fl \approx$ const. Then taking the entrainment of liquid into account may be reduced to the correction for the change of the coefficient of permeability $k_p$. In fact, the existence of entrainment requires additional expenditure of heat carrier into the zone of evaporation, i.e., increase of hydraulic resistance in regard to the liquid:

$$k_p^*=\frac{k_p}{1+\frac{\mathrm{const}_1}{\nu'}\sqrt{\frac{\sigma}{a\rho''}}}\,. \tag{17}$$

A preliminary evaluation of the magnitude of $\mathrm{const}_1$ corresponds to the value $4\cdot10^{-8}$.

With a view to the above-explained, the term of (16) assumes the form

$$q_m\nu' Fl/rk_p^* n\delta_{1a}P, \tag{18}$$

and we obtain the solution of (15) relative to $q_m$ in the form

$$Z=B_1\left(\sqrt{1+B_2Y}-1\right), \tag{19}$$

where

$$Z=\frac{q_m k_p^* Pn\delta_{1a}}{r\rho''\nu' Fl}\left[1+c_2 1.7n(1-\varepsilon)\frac{2.3-\varepsilon}{\varepsilon}\right]; \tag{20}$$

$$Y=\left[c_1\left(\frac{q_m}{r\rho''}\right)^2\rho''+c_3\left(\frac{4\sigma}{a}-\rho' gh\sin\beta\right)\right]\frac{1}{\nu'^2\rho''}\left(\frac{k_p^* Pn\delta_{1a}}{Fl}\right)^2\left(1+c_2 1.7n(1-\varepsilon)\frac{2.3-\varepsilon}{\varepsilon}\right); \tag{21}$$

$$B_1=1.9\cdot10^{-5};\ B_2=2.2\cdot10^{5}.$$

An evaluation according to the order of magnitude under the examined conditions shows that

$$\frac{4\sigma}{a}\gg\rho' gh\sin\beta,\ \frac{4\sigma}{a}\gg c_1\left(\frac{q_m}{r\rho''}\right)^2\rho'', \tag{22}$$

then Eq. (21), with its reduction to the saturation pressure $p_s$ = 0.1 MPa taken into account, is transformed in the following way:

$$Y_0 = \left(\frac{Fl}{k_p^* Pn\delta_{1a}}\right)^2 \frac{4\sigma}{a} \frac{\rho_0''}{\rho''} \left(1 + c_2 n 1.7 (1-\varepsilon) \frac{2.3-\varepsilon}{\varepsilon}\right). \quad (23)$$

The coefficient of permeability in (20) and (21) was calculated by the formula for uniform structures suggested at the Odessa Technological Institute of the Refrigeration Industry:

$$k_p^* = (0.03 - 0.05)\, a^{2.09}, \quad (24)$$

for nonuniform and arterial structures

$$k_p^* = \frac{\sum_i k_{pi}^* s_i}{\sum_i s_i},$$

where $s_i$ is the full cross-sectional area of the structure with the coefficient of permeability $k^*_{pi}$.

The experimental data for $q_m$ were processed in coordinates Z–Y with the value $c_2 = 1$. The results of the generalization are presented in Fig. 2.

## NOTATION

a, cell size; F, heating area; g, acceleration of gravity, specific consumption; h, height of capillary rise; k, coefficient; l, length; n, number of layers of a structure; P, perimeter of the heating surface; p, pressure; Q, heat flux; q, specific heat-flux density; r, specific heat of vaporization; w, velocity; δ, thickness of one layer of a structure; β, angle of slope; ε, porosity; ξ, coefficient of resistance; μ and ν, dynamic and kinematic viscosity, respectively; ρ, density; σ, specific surface anergy; φ, quantity of steam. Subscripts: m, maximal; s, parameters on the saturation line; en, entrainment; p, permeability; ', liquid; ", vapor; tr, transport.

## LITERATURE CITED


1. G. F. Smirnov and B. A. Afanas'ev, "Experimental investigation of heat exchange upon boiling in grid structures of heat pipes," Vopr. Radioelektron., Ser. TRTO, No. 2, 22-27 (1979).
2. G. P. Nikolaev and Yu. K. Tokalov, "Crisis of boiling on surfaces with porous coating," Inzh.-Fiz. Zh., 26, No. 1, 5-9 (1974).
3. A. P. Ornatskii, M. G. Semena, and V. I. Timofeev, "Experimental investigation of the maximal heat fluxes on flat metal-fiber filters under conditions characteristic of heat pipes," Inzh.-Fiz. Zh., 35, No. 5, 782-788 (1978).
4. P. D. Dan and D. A. Rey, Heat Pipes [Russian translation], Énergiya, Moscow (1979).
5. S. A. Kovalev, "Wave instability of nucleate boiling on a porous surface," in: Convective Heat Exchange. Methods and Results of Investigations, B. S. Petukhov (ed.), IVTAN, Moscow (1982), pp. 68-79.
6. S. S. Kutateladze, Fundamentals of the Theory of Heat Exchange [in Russian], Nauka, Novosibirsk (1970).
7. A. L. Koba, B. A. Afanas'ev, V. V. Zrodnikov, and G. F. Smirnov, Investigation of the Boiling of Liquids in Horizontal Plane Slits [in Russian], Manuscript deposited at VINITI, No. 1029-78, Moscow (1977).
8. G. F. Smirnov, Theoretical Foundations of Heat-Transferring Closed Evaporative Systems, Doctoral dissertation, LTIKhP, Leningrad (1979).
9. S. S. Kutateladze and M. A. Styrikovich, The Hydraulics of Gas–Liquid Systems [in Russian], Énergiya, Moscow (1976).
10. I. E. Idel'chik, Handbook of Hydraulic Resistances [in Russian], Mashinostroenie, Moscow (1975).