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TRANSFER OF STEAM IN THE POROUS COATING OF A HEATED CYLINDER SUBMERGED IN A LIQUID

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Data obtained in evaporation of propane in a porous coating on horizontally arranged copper cylindrical samples in the case of total and partial submersion in a liquid are analyzed. Using the dependences obtained by solution of the kinetic problems of mass transfer in capillaries, the number of macropores functioning as steam-discharge channels is determined.

Keywords: *porous structure, sintered copper powder, vaporization, gas flow in capillaries.*

Introduction. The phenomenon of phase transitions is widely used in heat exchanges for various purposes. Evaporation and boiling heat exchange is realized in power-generating units, refrigerators, chemical equipment, and electronic objects. One of the most efficient methods of increasing the intensity of phase-transition heat exchange is the deposition of a capillary-porous coating on the heating surface. Experiments show that in vaporization on a surface with a sprayed metal coating, the heat-transfer coefficients are 3 to 5 times higher than those on a uncoated surface and an order of magnitude higher in a porous layer sintered from copper powder [1, 2]. If the process occurs on a horizontal cylindrical surface, the heat-exchange intensity, in a certain range of heat loads, can be increased with a combined method of supplying the liquid phase to vaporization sites, i.e., a combination of pool conditions and capillary feed, by changing the height of the liquid level in relation to the heat-exchange surface [3].

In developing evaporation heat exchangers, one must not only evaluate the heat-exchange characteristics of porous heating surfaces but also determine the limiting heat loads under which the pores are drained. A considerable amount of experimental data on vaporization heat transfer in porous bodies has been accumulated at present. The procedure of computation of mass transfer in a porous matrix has been developed on the basis of this material and the steam flow rates for horizontal cylindrical samples with a copper-powder coating have been calculated for different heat-flux densities.

In the porous matrix, cavities between the contact areas of sintered metal-powder particles form a system of dead-end pores and interconnected channels of different flow sections. In channels with a small transverse dimension, the liquid is supplied, by capillary forces, to larger-diameter channels (macrochannels); the liquid is evaporated from the surface of curvilinear menisci in the microcapillary mouths. As the heat flux increases and the liquid-steam boundary moves into the sample, transport channels for removal of the steam (macrochannels) are formed.

To determine the steam-discharge characteristics of a capillary-porous heat-exchange surface we have developed a computational procedure; in creating it, we used experimental results obtained at the A. V. Luikov Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus. The structure of the experimental bench has been described in [2]. The working portion with a test sample was arranged in a stainless-steel evaporation chamber; it was placed in a thermostatted box to ensure adiabatic conditions. The heat flux to the heat-exchange surface was supplied from the electric heater within the sample; measurements were performed in a steady-state regime. The obtained information was recorded and processed with a special program of an automated unit incorporating instrumentation equipment and a personal computer [4].

In developing the procedure, we have analyzed experimental data obtained in evaporation of propane in a porous coating on copper cylindrical samples of diameter 20 mm and length 100 mm (which were arranged horizontally) in the case of total and partial submersion of a cylinder in a liquid to a depth h equal to half, three quarters of the

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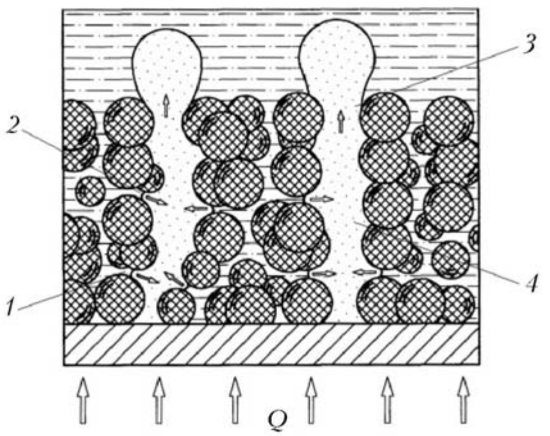

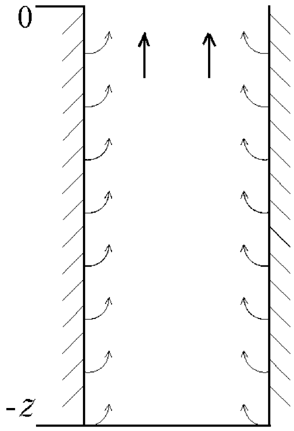

Fig. 1. Surface element with a sintered powder coating: 1) microchannel; 2) meniscus; 3) macrochannel; 4) vapor bubble.

Fig. 2. Geometric scheme of the kinetic problem. The semiinfinite cylindrical channel.

diameter, and the total diameter of the cylinder. The coating was manufactured from PMS-N copper powder; the particle diameter was 63 to 100 μm; the open porosity amounted to 50–55%.

Using the dependences obtained by solution of the kinetic problems of mass transfer in capillaries and experimental results we determine the number of macropores functioning as steam-discharge channels.

Mass Transfer in the Porous Coating in Vaporization. During the experiment, we visually observe three regimes of heat exchange: free convection, the transient regime, and intense vaporization. The length of the existence domains of these regimes is dependent on saturation pressure and on the presence of a porous coating on the exterior tube surface and the parameters of the coating. When mass transfer is analyzed the porous coating is considered as a system of large and small channels analogously to the model described in [5, 6]. The liquid in the inhomogeneous porous coating is supplied, by capillary forces, via smaller-size pores to large pores; evaporation is from the surface of curvilinear menisci at the capillary mouths, and the steam is removed through these macrochannels to the porous-structure surface (Fig. 1). It is noteworthy that fairly large thicknesses of porous coatings are characterized by structural regularity [7], i.e., by the uniformity of the pore distribution over the filtering surface. As the layer thickness decreases, we have a shift toward structural irregularity, i.e., when a fine structure is shaped the probability that transport pores cropping out at the surface of the porous body will be formed grows.

To describe mass transfer in the porous coating in vaporization in it we use results of the problem of the kinetic theory of mass transfer in a capillary in evaporation from the interior surface [8, 9]. Such problems of the kinetic theory of gases differ significantly from the analogous problems of gasdynamics in a channel in injection or suction through the lateral surface, when the flow rate of the gas through the lateral channel surface is usually assumed to be known and solution of Navier–Stokes equations with corresponding boundary conditions presents no fundamental difficulties. In the problem in question, the gas flow rate on the interior surface of the channel is not known in advance and must be determined as a result of solution.

We consider stationary steam flow in a semiinfinite ($z < 0$) cylindrical channel of radius r_0 (Fig. 2) on whose open end ($z = 0$) a constant pressure p_a lower than the saturated-steam pressure $p_e(T)$ is maintained. We have evaporation on the entire interior channel surface of constant temperature T.

The motion of the gas is investigated from the model kinetic BGK (Bhatnagar–Gross–Krook) equation written in dimensionless form:

$$\boldsymbol{\xi}_r^* \frac{\partial \bar{f}}{\partial \mathbf{r}} + \xi_z^* \frac{\partial \bar{f}}{\partial z} = \beta \left(\bar{f}_0 - \bar{f}\right) , \tag{1}$$

where

$$\beta = \frac{r_0}{\Lambda} = \frac{1}{\mathrm{Kn}}\,, \quad \bar{f} = \frac{f}{n_{\mathrm{e}}}\left(\frac{2kT}{m}\right)^{3/2}\,, \quad \bar{f}_0 = \frac{n}{\pi^{3/2}}\exp\left[-\left(\boldsymbol{\xi}^* - \mathbf{c}\right)^2\right]\,, \quad n = \frac{p}{n_{\mathrm{e}}kT}\,,$$

$$\boldsymbol{\xi}^* = \boldsymbol{\xi}\sqrt{\frac{m}{2kT}}\,, \quad \mathbf{c} = \frac{1}{\pi^{3/2}}\int_{-\infty}^{\infty} \boldsymbol{\xi}^* \bar{f} d\boldsymbol{\xi}^*\,.$$

The boundary equation for Eq. (1) is as follows: the distribution function of molecules leaving the lateral channel surface (i.e., of evaporated molecules) is Maxwellian with a density $n_{\mathrm{e}}(T)$:

$$\bar{f}\left(\xi_r^* < 0\right) = \frac{1}{\pi^{3/2}}\exp\left(-\xi^{*2}\right)\,. \tag{2}$$

The solution of problem (1) and (2) is sought in the form

$$\bar{f} = \frac{1}{\pi^{3/2}}\exp\left(-\xi^{*2}\right)\left[1 + V(z)\,\varphi\left(\boldsymbol{\xi}^*, r\right)\right]\,,$$

where $V(z)$ and $\varphi(\xi^*, r)$ are the sought functions. We introduce the notation

$$g = \int_{-\infty}^{\infty} \exp\left(-\xi^{*2}\right)\varphi d^3\xi^*\,, \quad f_i = \int_{-\infty}^{\infty} \exp\left(-\xi^{*2}\right)\varphi \xi_i^* d^3\xi^*\,, \quad i = x, y, z\,.$$

The particle density $n(z, r)$ and the molecular-flux densities $\bar{j}_{n,i}(z, r)$ are found in the following manner:

$$n\,(z, r) = 1 + (n_{\mathrm{a}} - 1)\exp\,(\mu z)\frac{g\,(r)}{2\int_0^1 grdr}\,, \quad \overline{j_{n,i}}\,(z, r) = nc_i = (n_{\mathrm{a}} - 1)\exp(\mu z)\frac{f_i\,(r)}{2\int_0^1 grdr}\,, \quad z < 0\,.$$

The unknown functions f_i and g and the parameter $\mu(\beta)$ are determined by solution of the system of integral equations [8] for any values of the Knudsen number. For high β values, i.e., in the regime of a continuous medium, we obtain an analytical expression for the gas flow average over the channel cross section at the pore mouth ($z = 0$):

$$\bar{j}_n\,(0) \approx (1 - n_{\mathrm{a}})\frac{\sqrt{\beta}}{2\pi^{1/4}}\,, \tag{3}$$

and the parameter μ is approximately equal to $\frac{4}{\pi^{1/4}}\frac{1}{\sqrt{\beta}}$. The coefficient $\frac{1}{\mu}$ characterizes the depth of the zone of effective evaporation. We write expression (3) in dimensional form for the mass flux j, using the relations

$$n_{\mathrm{a}} = \frac{p_{\mathrm{a}}}{n_{\mathrm{e}}kT}\,, \quad n_{\mathrm{e}} = \frac{p_{\mathrm{e}}}{kT}\,, \quad \bar{j}_n\sqrt{\frac{2kT}{m}} = j_n\,.$$

Then we have

$$j = n_{\mathrm{e}}mj_n = m\sqrt{\frac{2kT}{m}}\,\frac{p_{\mathrm{e}} - p_{\mathrm{a}}}{kT}\,\frac{\sqrt{\beta}}{2\pi^{1/4}} = \frac{p_{\mathrm{e}} - p_{\mathrm{a}}}{\sqrt{2\pi\frac{kT}{m}}}\sqrt{\beta}\,\pi^{1/4}\,. \tag{4}$$

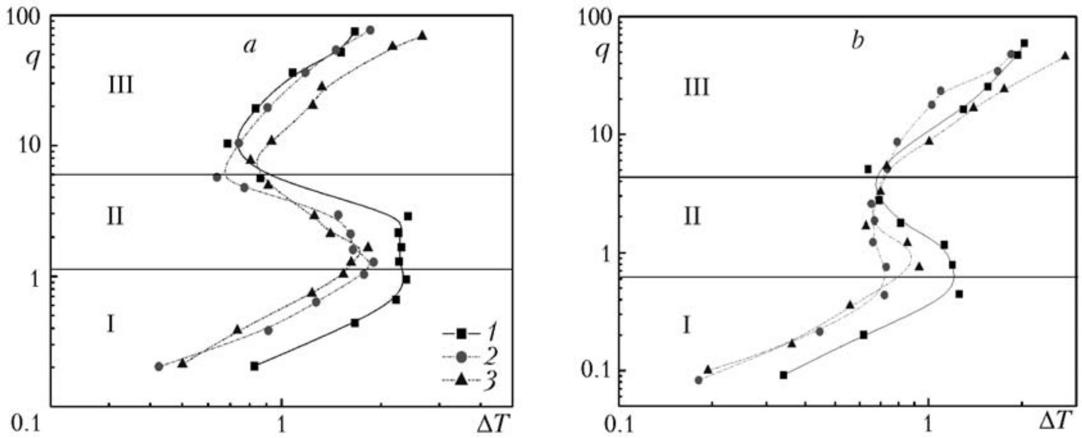

Fig. 3. Experimental data on superheatings of the heat-exchange surface for samples with a porous-coating thickness of 0.3 mm (a) and 0.6 mm (b): 1) h = 20, 2) 15, and 3) 10 mm. q, kW/m^2; ΔT, ^{o}C.

Since formula (4) has been obtained for the isothermal interior channel surface, in what follows we take $p_e = p_e(T_0)$ and $p_a = p_e(T_{sat})$, where T_0 is the steam temperature in the capillary and T_{sat} is the saturation temperature in the volume. With allowance for this fact, formula (4) takes the form

$$j = \frac{p_e(T_0) - p_e(T_{sat})}{\sqrt{2\pi \frac{kT_0}{m}}} \sqrt{\beta}\, \pi^{1/4} . \tag{5}$$

Figure 3 shows the superheating of the surface as a function of the density of the supplied heat flux. Portion I corresponds to free convection in the liquid. Vaporization is absent from this regime. The bends of the curves on portion II correspond to the beginning of vaporization where the formed steam bubbles move to the external boundary of the porous coating. Intense steam generation is observed on portion III. The steam goes out via the channel formed by the macropores (see Fig. 1).

In comparing to the experimental data, we make the following assumptions:

1. The entire heat flux supplied to the base of the capillary-porous structure is expended in evaporating the liquid (absence of heat loss):

$$j_{exp} \approx \frac{q}{r^*} . \tag{6}$$

2. The steam-discharge channels represent exposed cylindrical capillaries.

3. The steam temperature in the capillary is assumed to be constant and equal to the averaged temperature $T_0 = (T_s + T_{sat})/2$.

4. At high heat loads, it is assumed that capillaries in the not submerged part of the structure are drained and do not participate in steam removal.

In calculation of vaporization mass transfer in the porous coating, we will use formulas (5) and (6) and determine the number of channels via which the generated steam is removed from the porous coating. To determine the total mass flux per unit upper surface of the porous layer we write expression (5) in the following form:

$$j_{exp} = \varepsilon_t \frac{p_e(T_0) - p_e(T_{sat})}{\sqrt{2\pi \frac{kT_0}{m}}} \sqrt{\beta}\, \pi^{1/4} , \tag{7}$$

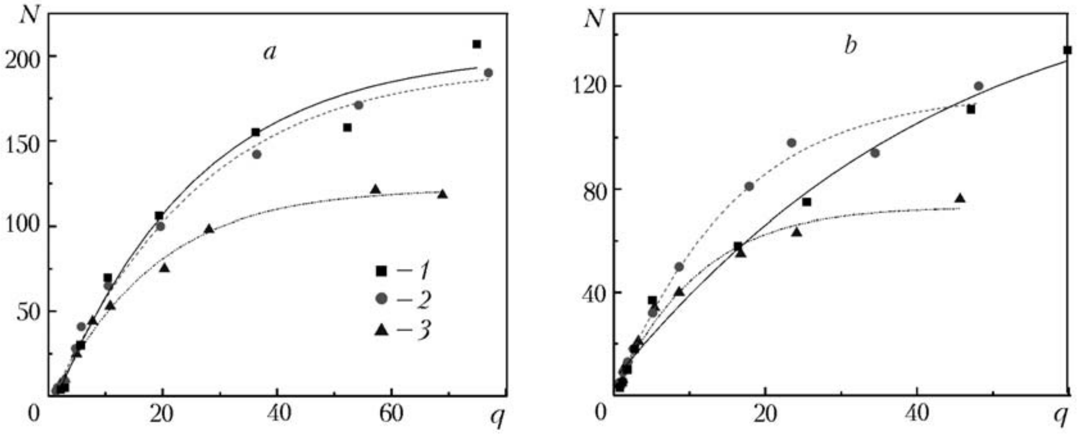

Fig. 4. Number of steam-discharge channels per unit heat-exchange surface of the samples with a coating thickness of 0.3 mm (a) and 0.6 mm (b): 1) h = 20, 2) 15, and 3) 10 mm. N, 10^3 m^{-2}; q, kW/m^2.

where ε_t is the ratio of the total area of the steam-discharge channels to the cylinder surface (transport porosity):

$$\varepsilon_t = \frac{S_{\text{ch}}}{S_{\text{c}}} = \frac{sN_{\text{ch}}}{S_{\text{c}}} . \tag{8}$$

Here, S_{ch} is the total cross-sectional area of the steam-discharge channels, S_{c} is the surface area of the cylinder, and N_{ch} is the number of large pores for removal of the generated steam. Substituting (8) into (7), with account for expression (6) we obtain

$$N_{\text{ch}} = \frac{q}{r^*} \frac{\sqrt{2\pi^{1/2} \frac{k}{m} T_0}}{(p\,(T_0) - p\,(T_{\text{sat}}))\sqrt{\beta}} \frac{S_{\text{c}}}{s} . \tag{9}$$

Figure 4 gives the numbers of channels via which the steam is removed per unit surface as functions of the densities of the supplied heat flux for samples with a coating thickness of 0.3 and 0.6 mm for different submersion depths. The saturation temperature in the experiments is T_{sat} = 20°C; the saturation pressure is $p_{\text{sat}} = 8.4 \cdot 10^5$ Pa.

Let us consider computation of the required number of channels with an example. For a sample with a coating thickness δ = 0.3 mm, which is totally submerged in a liquid, the superheating is 1.08°C for the heat flux q = 36.25 kW/m^2. We take an average hydraulic diameter of 24 μm as the characteristic dimension. We have the parameter $\beta = \frac{1}{\text{Kn}}$ = 2720. The surface area of the cylinder with allowance for the structural thickness is $S_{\text{c}} = 6.47 \cdot 10^{-3}$ m^2; the cross-sectional area of the channel is $s = 4.7 \cdot 10^{-10}$ m^2. With allowance for the vaporization heat $r^* = 3.43 \cdot 10^5$ J/kg and $p(T_0 = 20.54^\circ\text{C}) = 8.56 \cdot 10^5$ Pa, we obtain the required number of steam-discharge channels per unit surface $N = 154 \cdot 10^3$ m^{-2}.

Conclusions. According to the obtained results, the number of steam-discharge channels in the considered range of heat loads grows with heat-flux density q. However, the slope of these curves decreases and the number of channels via which the steam is discharged approaches a maximum.

Here we give the following explanation. The change in the calculated number N as a function of q for this porous structure is due to the fact that the mass flux of the steam j is determined for the average (fixed) radius of a large pore. In actual practice, a radial distribution of steam-discharge channels exists in each specific porous structure, and the contribution of channels whose radii are close to the selected average radius to the total flux j increases with q, i.e., the (radial) range of channels ensuring steam discharge for a given q is extended.

For the sake of comparison it is of interest to note that in [10] leaves of plants are considered as polycapillary bodies having macro- and micropores where the macropores are the channels through which the aeration of cells is carried out, whereas the micropores are the channels via which the liquid moves under the action of capillary and osmotic potentials. The number of mouths per 1 cm^2 of the lower part of a leaf attains several thousands.

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NOTATION

c, dimensionless macroscopic gas velocity; $f(\xi, r, z)$, molecular-velocity distribution function; $\bar{f}_0$, Maxwellian distribution function; j, mass flux of the steam, $\text{kg/(m}^2\cdot\text{sec)}$; $\bar{J}_i(z, r)$, molecular-flux density; h, submersion depth, mm; $k = 1.38\cdot10^{-23}$ J/°C, Boltzmann constant; Kn, Knudsen number; m, weight of a steam molecule, kg; n_{e}, particle density; n, dimensionless gas density; N, number of large pores per unit surface, m^{-2}; N_{ch}, number of large pores; p, pressure, Pa; p_{a}, channel pressure, Pa; p_{e}, saturated-steam pressure, Pa; q, heat-flux density, kW/m^2; Q, heat flux, W; r, z, coordinates, m; r_0, channel radius, m; r^*, latent vaporization heat, J/kg; s, cross-sectional area of the channel, m^2; S, area, m^2; T, temperature, °C; β, parameter; δ, coating thickness, mm; ε, porosity; Λ, mean free path of molecules, m; μ, parameter; ξ, velocity vector of gas molecules; ξ^*, dimensionless velocity vector of gas molecules. Subscripts: a, channel inlet; e, saturated steam; ch, steam-discharge channels; s, cylinder-wall surface; sat, saturated; t, transport; c, cylinder; exp, experimental.

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