EXPERIMENTAL INVESTIGATION OF HEAT TRANSFER WITH EVAPORATION OF THE AGENT FROM A CORRUGATED CAPILLARY STRUCTURE

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The authors present experimental data on the intensity of heat transfer in a corrugated capillary structure. They propose a physical model of the heat-transfer process that explains the results obtained.

Capillary porous structures already find use as coatings to provide intense heat transfer under conditions of thin-film evaporation or boiling on a heated surface. For example, the exclusively large heat conduction of heat pipes is due, in particular, to the high intensity of the heat-transfer processes occurring in the capillary structures in the evaporation and condensation zones. The calculated values presented in [1] are evidence that in the evaporation of low-temperature heat-transfer agents from finely porous capillary structures one can reach heat-transfer coefficients on the order of 10^4–10^5 W/m^2·K and heat-flux densities in excess of critical for boiling in a volume. By using capillary structures in a system for cooling laser mirrors one can employ water to remove heat fluxes of 10^7 W/m^2 and more [2].

This paper presents results of an experimental investigation of heat transfer on a surface with a capillary-porous coating made of corrugated nickel mesh [3]. The technology of making a corrugated capillary structure is quite simple, and at present it is already used in heat-pipe practice [4]. By obtaining data on heat-transfer intensity and comparing these data with values for other known structures, we can evaluate the desirability and the efficiency of the use of a corrugated structure.

Experimental Equipment. The test of the corrugated capillary structure was conducted on a facility designed for investigation of heat-transfer processes with evaporation of liquid on the surface of test specimens and including a working section with a level control tank, and also systems for vacuum, control of electric heating, and thermometry. The construction of the working section is shown in Fig. 1. The working section was made in the form of a demountable cylindrical chamber, connected by lines 1 and 2 with the level control bath and the vacuum system. There were viewing windows 3 in the chamber for visual observations. The temperature conditions in the working section were controlled with the electric heater 4 and the condenser 5. The temperatures were monitored with the aid of a moving heat sensor inserted into the vapor volume via the capillary 6.

The corrugated capillary structure 7 was set up at the level of the viewing windows and was pressed against the heated copper substrate 8, made in the form of a plate of size 40 × 40 × 2.5 mm, by a device made of heat-insulating material (not shown in Fig. 1). The film heater 10 was pressed against the underside of the substrate via an electrically insulating layer by means of the elastic element 9. The structure–substrate–heater assembly was mounted on the heat-insulating base 11. The wall temperature below the corrugated structure was measured by means of heat sensors attached to the substrate.

The capillary structure was made up by corrugating nickel mesh of thickness 0.12 mm with an effective pore size of 18 μm. The fabrication technology is simple and is used at present in industrial production. The result of the corrugating is to form a system of parallel capillary channels of height 1 mm, and the mean width of adjacent channels is different: the narrow channels are 0.2 and the wide channels are 0.6 mm (Fig. 2a). In this structure the liquid is transported along the capillary channels and the mesh, which has a high capillary head, but a low permeability along the base.

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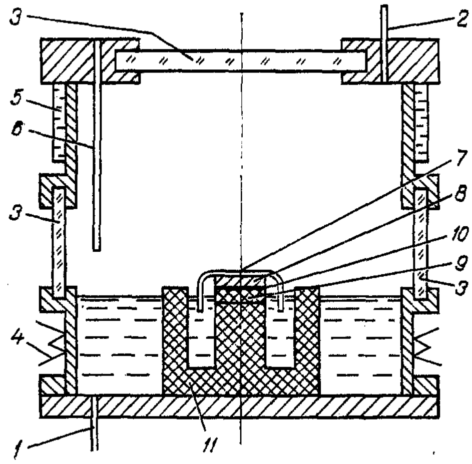

Fig. 1. The working section.

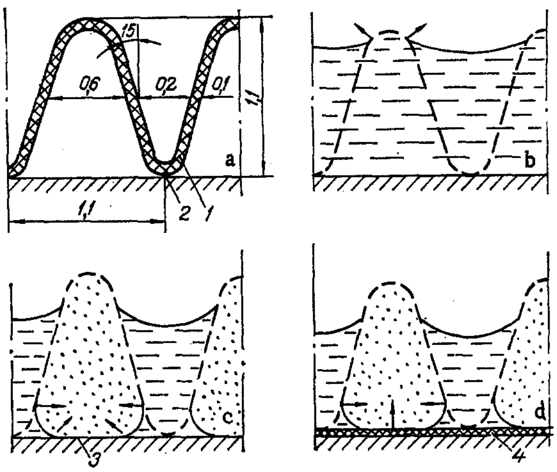

Fig. 2. Evaporation from the corrugated capillary structure: a) the structure; b) the low heat-flux regime; c) the high-power regime; d) the corrugated structure with an intermediate mesh layer: 1) corrugated mesh: 2) wall; 3) dried part of the wall; 4) mesh.

The corrugated structure of size 40 × 80 mm with channel direction along the large generator was pressed against the substrate, and both ends of the structure were immersed in the liquid, whose level was below the surface of the substrate. Thus, the transport of liquid to the heat-transfer surface was accomplished by capillary forces. The position of the structure on the substrate surface was such that the narrow channels were open to the vapor volume, and the wide channels were adjacent to the wall. This position of the channels was preferable, since it allowed the required supply of liquid to the heat-transfer surface, and removal of vapor along the internal channels if they were steaming.

In the second stage of the experiment, in order to increase the heat-transfer intensity we placed a thin layer of fine-cell brass mesh of square weave between the corrugated structure and the substrate. Distilled water was used as the heat-transfer agent in the facility.

Experimental Results. During the experiment we investigated the dependence of the heat-flux density on the wall—vapor temperature drop. The flux density varied from zero to the critical valus corresponding to dry-out of the structure and a sharp increase of wall temperature. The basic temperature condition of the experiment was 300°K; with increase of temperature the heat-transfer coefficient increased, but the nature of the dependence $\alpha(q)$ was preserved. The dependence varied numerically, but was maintained qualitatively also with change of the liquid level. Therefore, we have presented experimental data for a single

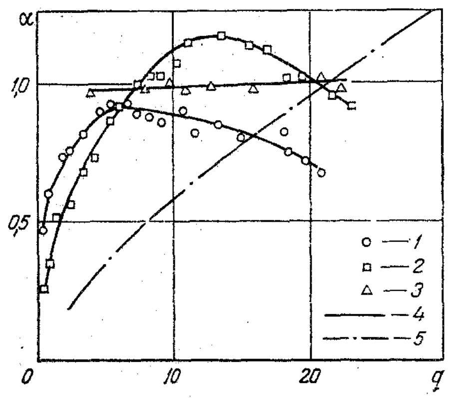

Fig. 3. The heat-transfer coefficient as a function of the heat-flux density: 1) corrugated structure; 2) corrugated structure with intermediate mesh layer; 3) rectangular channels of size 0.3 × 0.8 mm; 4) mean curves; 5) calculated curve for boiling on a smooth surface [7]. The units of α are 10^4 W/m²·K; and the units of q are 10^4 W/m².

level of 9 mm below the heat-transfer surface. According to a calculation, hydrostatic dry-out of the wide channels sets in at a height difference of 30-35 mm.

Figure 3 shows the heat-transfer coefficient as a function of the heat-flux density. As follows from the experiment, with increased heat flux the heat-transfer coefficient increases, reaches a maximum, and then begins to fall. This behavior can be explained by analyzing the heat-transfer mechanism in a corrugated structure.

At low heat flux the liquid occupies practically all of the structure (Fig. 2b), and the heat transfer is accomplished by heat conduction through the layer of liquid and the corrugated mesh. The contribution of the mesh to the heat-flux transport can be estimated from the ratio $\lambda_m\delta_m/\lambda_l\delta_l$. For the given structure this ratio is 20, i.e., the thermal resistance of the mesh is considerably less than that of the liquid cell, and therefore, a large part of the heat flux is transported to the mirror by evaporation over the mesh. On the substrate surface there is a uniform temperature distribution with a maximum at the center of a wide corrugation. Where the mesh touches it the wall temperature is lowered. The heat is transferred from this region along the mesh to the part of the corrugation protruding into the vapor. The effective resistance of the filled structure is quite large, which explains the low value of heat transfer at low heat flux.

With increase of heat-flux density the hydraulic losses in the structure increase, which leads to an increase of the curvature of the meniscus and deepening of the liquid in the narrow channels. Here the thermal resistance of the filled structure falls, and the heat-transfer intensity increases.

At a specific heat-flux density the wall heating reaches the critical value and there is boiling of the heat-transfer agent in the wide channels. The fine-porous mesh wetted by the liquid inhibits direct efflux of vapor, and therefore the vapor phase is ejected from the capillary structure along the wide channels. At first the process is unstable — there is a pulsed boiling regime. At increased heating the process stabilizes: the wide channels dry out and function as vapor generators, and the liquid filling the narrow channels forms stable menisci between the wall and the mesh in the corners of the wide channels (Fig. 2c).

Under these conditions the evaporation occurs mainly in the wide channels, and to a lesser extent in the vapor volume region of the chamber. Here the most intense evaporation process occurs in the section of the surface of the meniscus immediately adjacent to the heated wall. For the structure without an intermediate mesh layer the heat-transfer coefficient reaches $9 \cdot 10^3$ W/m²·K.

With further increase of power there is deepening of the meniscus in the corner between the wall and the mesh. The deepening is due to an increased curvature of the surface which is linked, first with an increase of the hydraulic loss in the liquid, and secondly, with an increase of pressure loss in the vapor flowing out along the wide channels. The force balance equation for the meniscus can be written in the form

$$1+\frac{\Delta P_{v,i}}{\Delta P_{\sigma,n}}+\frac{\Delta P_{v,\xi}}{\Delta P_{\sigma,n}}=\frac{\Delta P_{\sigma,m}}{\Delta P_{\sigma,n}},$$

where the quantity $\Delta P_{\sigma,n}$ corresponds to the transport pressure losses in the liquid, and is determined by the available capillary head of the narrow channels. At the central section of the test region where the pressure drop values are greatest the limiting value of the transport losses with respect to the liquid may be calculated approximately according to the average width of the narrow channels.

Estimates indicate that under precritical conditions the relative value of the inertial losses with respect to the vapor $\Delta P_{v,i}/\Delta P_{\sigma,n}$ is ~ 0.3, and the friction loss $\Delta P_{v,\xi}/\Delta P_{\sigma,n} \approx 1$, i.e., in total the ratio $\Delta P_{\sigma,m}/\Delta P_{\sigma,n} \simeq 2.3$. This means that if the limiting radius of curvature on the interphase surface in the narrow channel is roughly 100 μm, the radius of curvature of the meniscus located between the wall and the mesh in the corner of the wide channel is 40 μm. Taking into account that the wetting angle for water on the copper wall lies in the range 45–70°, and also accounting for the data [5] on the increase of effective boundary angle in the presence of heat transfer on a surface, one can assume that there is a strong deepening of the meniscus considered, and therefore, the dried out part of the wall surface may be relatively large. An increase of the fraction of dried out surface with increase of heating leads to an increase of the mean-integral wall temperature and a decrease of the heat-transfer coefficient under conditions close to critical.

In order to wet the dried out surface and to increase the heat-transfer coefficient in the increased heat load region in the second stage of the experiment we set up a thin layer of brass mesh of square weave (Fig. 2d) between the corrugated structure and the substrate. As a result the maximum heat-transfer coefficient ($\alpha_{max} \simeq 1.2 \cdot 10^4$ W/m²·K) moved to the region of increased heat transfer, and on the whole the heat-transfer intensity in this region increased by 30–40% (Fig. 3). Nevertheless, at a heat-flux density of more than $1.4 \cdot 10^5$ W/m² the heat-transfer intensity begins to fall, although the heat transfer increases right up to the onset of critical conditions in the structure with no intermediate layer of mesh. The drying out of the capillary structure in both forms of structure begins roughly at the same heat flux level ($(2.1–2.3) \cdot 10^5$ W/m²), which is evidence that they have a common critical mechanism, apparently associated with the transport capabilities of the corrugated structure. Here one should take into account that the limiting permeability of the fine-porous thin mesh packed on to the substrate is low, and therefore, the transport capability of the structure as a whole is practically unchanged.

An examination of the copper substrate conducted after the first stage of the experiment showed the presence of bands of deposition, laid down in the direction of the corrugations. This agrees with the postulated heat-transfer model, if we take into account that there is constant mass transfer to the evaporating meniscus zone.

An estimate of the effectiveness of using the corrugated capillary structure can be made in comparison with other known structures. Figure 3 shows the data obtained by the authors on heat-transfer intensity with evaporation of water from a system of rectangular capillary channels cut in a copper wall with a pitch of 0.8 mm. The width of the channels is 0.3 and the depth 0.8 mm. Such structures are widely used in heat pipe practice. The heat-transfer coefficient of the test structure with channels lies at the level 10^4 W/m²·K, i.e., the heat-transfer intensity with evaporation from a corrugated structure is on the same order as for systems of capillary channels with an average pitch of cutout. Systems with a fine pitch have higher values of heat-transfer coefficient.

The authors of [6] investigated evaporation of water from a nickel metal–fiber structure pressed mechanically against a copper wall. At the heat-transfer level of 10^5 W/m² the heat-transfer coefficient was roughly 10^4 W/m², i.e., on the same order as the corrugated structure. Similar results were obtained with boiling of water in nickel metal–fiber structures welded to a nickel wall. However, with boiling of water in structures welded from copper fibers, the heat-transfer coefficient can reach $4 \cdot 10^4$ W/m²·K.

Comparing the intensity of the processes of evaporation from the corrugated structure and boiling on a smooth surface [7], one can say that in the moderate heat-flux region the evaporation from the corrugated structure is more intense, but that in the high flux region the surface boiling process is more intense.

Thus, a comparison of a corrugated structure with other known arrangements shows that this structue can be used as a capillary-porous coating to achieve rather intense heat transfer in the evaporation regime. When one used corrugated structures in heat pipes one must provide a system of apertures in the upper part of the corrugations for efflux of vapor.

NOTATION

$\Delta P_{\sigma,m}$, liquid—vapor pressure drop at the wall meniscus; $\Delta P_{\sigma,n}$, transport pressure losses in the liquid; $\Delta P_{v,i}$, $\Delta P_{v,\xi}$, inertial and friction pressure losses in the vapor; q, heat-flux density; α, heat-transfer coefficient; δ_m, mesh thickness; δ_l, average width of the liquid cell; λ_m, effective heat conduction of the mesh; λ_l, thermal conductivity of the liquid.

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