## NOTATION

D, W, depth and half width of the grooves; $L_1$, half width of the fin between grooves; L, length; $\alpha$, heat-transfer coefficient; $Q_{max}$, maximum heat flux; q, heat flux density; R, radius; $\phi$, slope angle; $\delta$, maximum thickness of the porous layer. Subscripts: e, evaporator; c, condenser; a, adiabatic; v, vapor; ex, external.

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# HEAT-EXCHANGE INTENSITY IN BOILING AT SURFACES WITH POROUS CLADDINGS UNDER CAPILLARY TRANSPORT CONDITIONS


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UDC 536.423.1:621.59



The results of an experimental investigation of the heat-exchange intensity in boiling at surfaces covered with porous, metal-fiber claddings under capillary transport conditions are described.


Capillary-porous claddings are used on an ever-increasing scale in heat-exchange devices of various types in order to ensure capillary transport of the liquid and also intensify the heat exchange during phase transitions of the coolant. The results obtained in investigating the hydrodynamic and heat-exchange processes occurring in capillary structures have been treated exhaustively in [1-3] and other studies. However, relatively little attention has been paid in these investigations to the heat-exchange intensity in coolant boiling under capillary transport conditions. The results obtained in [4-7] and many other papers are uncoordinated and contradictory. For instance, the heat-exchange intensity is independent of the porous cladding thickness according to data supplied by some authors, while it depends on this thickness according to others; meanwhile, the exponent n of the thermal flux density in the expression $\alpha = f(q)$ varies from 0.12 to 0.7. This line of research does not include comprehensive investigations of the effect of the geometric, thermophysical, and structural characteristics of porous claddings on the heat exchange intensity in boiling.

Our aim was a thorough investigation of the effect of the parameters of porous metal-fiber structures on the heat-exchange intensity in the boiling of water, acetone, and ethyl alcohol under capillary feed conditions at saturation pressures in $(0.5\text{-}0.98)\cdot 10^5$ Pa range.

The experimental investigation was performed by means of the device whose operating section is shown in Fig. 1a, using specimens of capillary metal-fiber structures (Fig. 1b). The characteristics of the specimens are given in Table 1. Each specimen consists of a base-layer 5 with a diameter of 35 mm and a thickness of 3 mm and an oxidized capillary structure 6 with a diameter of 105 mm, sintered onto the base-layer surface. The junctions of six copper-constantan thermocouples 9, coated with a Teflon lacquer, are embedded in grooves 13 of the base layer. The lead-out of the thermocouples from glass cylinder 4 is provided through Teflon sheaths and a hermetic lead-out from flange 7. In order to eliminate the


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TABLE 1. Characteristics of the Specimens

| Specimen No. | Material | | Characteristics of porous cladding | | |
|---|---|---|---|---|---|
| | base-layer | fibers | $\delta$, mm | $\Pi$ | $\lambda_f$, W/(m·°K) |
| 1—31 | M-1 copper | M-1 copper | 0,4; 0,6; 0,8; 1,0; 2,0; 4,0; 5,0; 6,0; 9,0; | 0,2; 0,4; 0,5; 0,6; 0,7; 0,8; 0,85 | 2,1—178 |
| 32—35 | M-1 copper | N-1 nickel, 9Kh18N9T steel | 1,3; 2,5; 2,9; 7,2 | 0,87; 0,9; 0,91 | 0,056—0,57 |
| 36—38 | 9Kh18N9T steel | 9Kn18N9T steel | 0,4; 1,0; 3,2 | 0,7; 0,9 | 0,069—0,64 |

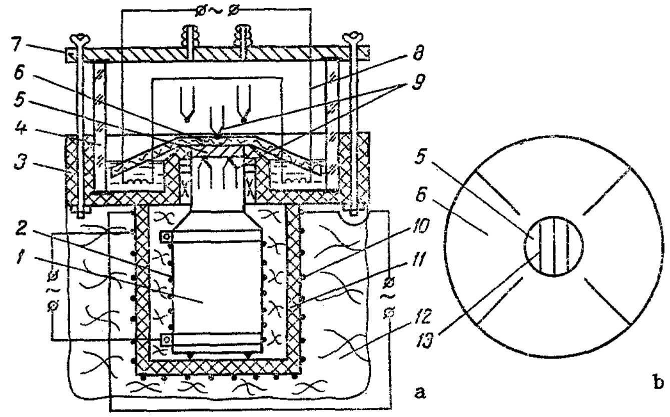


Fig. 1

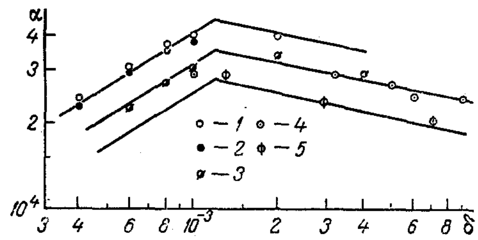


Fig. 2

Fig. 1. Operating section of the experimental device (a) and view from below of a specimen (b).

Fig. 2. Heat-exchange coefficient in boiling as a function of the porous cladding thickness ($q = 5 \cdot 10^4$ W/m², $p_{sat} = 0.98 \cdot 10^5$ Pa). Copper-fiber specimens: 1) $\Pi = 0.4$; 2) 0.5; 3) 0.8; 4) 0.85; specimens made of stainless-steel fibers: 5) $\Pi = 0.91$; the curves were obtained by calculations based on Eq. (1); $\alpha$[W/(m²·°K)]; $\delta$[m].

thermal contact resistance, the specimen is fastened by brazing the base-layer to the end-face of copper rod 1. The design of the operating section provides for two copper rods whose masses differ from each other by one order of magnitude. The operating liquid in the Teflon container 3 is heated to the saturation temperature by means of heater 8. The liquid is kept constantly at a level 5-6 mm below the base-layer's upper end-face. The heat loss of heater 2 is reduced to a minimum by using a protective heater 10, an Alundum container 11, and heat insulation 12.

In the course of experiments, each specimen was broken in by boiling over a period of 12-16 h. The base-layer temperature T and the saturation temperature $T_{sat}$ were measured by means of an Shch68001 digital voltmeter, while the supplied thermal flux density was measured by means of a D592 wattmeter. The temperature head $\Delta T$ was determined with respect to the readings of three thermocouples in the vapor volume, which were located at a distance of 1-5 mm from the surface of the structure (the readings of the three thermocouples virtually coincided with each other), and with respect to the averaged readings of the six thermocouples in the specimen's base layer with an allowance for the temperature drop between the location of thermocouple junctions and the joint between the surface and the capillary structure. The high accuracy in measuring the thermal flux was confirmed by calorimetric measurements of the operating section of the device.

The effect of the capillary structure's thickness on the heat exchange intensity was measured in the first series of experiments. The experiments were performed on six batches of specimens, Nos. 1-31, with identical structural and thermophysical characteristics of porous claddings in each of the batches which consisted of four to six specimens. The characteristic relationship between the heat exchange coefficient and the structure's thickness in water boiling on copper base-layers under capillary transport conditions is shown in Fig.

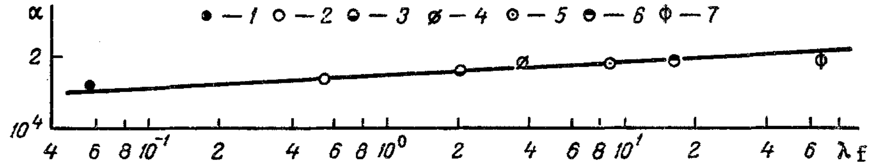


Fig. 3. Dependence of the heat-exchange coefficient in water boiling under capillary transport conditions on the thermal conductivity of the cladding framework ($q = 2 \cdot 10^4$ W/m², $p_{sat} = 0.98 \cdot 10^5$ Pa). Specimens made of stainless-steel fibers: 1) $\Pi = 0.91$, $\delta = 2.9$ mm; nickel-fiber specimens: 2) 0.87 and 2.5 mm; copper-fiber specimens: 3) 0.85 and 3.2 mm; 4) 0.8 and 2 mm; 5) 0.7 and 2 mm; 6) 0.6 and 2 mm; 7) 0.4 and 2 mm; the curve has been obtained by calculations based on Eq. (1) for $\delta = 2.5$ mm. $\lambda_f$, W/(m·°K).

2. Heat exchange intensity first increases with the thickness of the capillary structure and subsequently diminishes throughout the investigated ranges of the operating parameters and the structural and thermophysical characteristics of the claddings. The exponent m in the $\alpha = f(\delta)$ relationship is equal to 0.65 for cladding thicknesses of 0.4-1.2 mm, while $m = -0.2$ for specimens with $\delta > 1.2$ mm.

In performing the second series of experiments, we investigated the effect of the thermal conductivity of the porous structure's framework and of the heating surface material on the heat exchange intensity. Analysis of experimental data indicates that the heat exchange coefficient depends on the thermal conductivity of the porous cladding's framework (Fig. 3); however, this dependence is not strongly pronounced ($\alpha \sim \lambda_f^{0.07}$). The thermal conductivity values of the framework of metal-fiber structures were calculated on the basis of the recommendations given in [3].

The physical characteristics of the heating surface exert a considerable effect on the heat-exchange intensity. Thus, in liquid boiling at a stainless-steel base-layer, the heat-exchange coefficient amounts to almost one-half of that at a copper heating surface with the same characteristics of the porous cladding. If we use the coefficient of heat retention by the surface material for determining the effect of the heating surface characteristics on the heat exchange in boiling under capillary transport conditions, it follows on the basis of experimental data that $\alpha \sim (\sqrt{\lambda_m c_m \rho_m})^{0.4}$.

In the third series of experiments, we investigated the effect of the structural characteristics of the capillary-porous cladding on the heat-exchange intensity. The structure porosity $\Pi$, the pore dimensions D, and the distribution of pore sizes $N = f(D_i)$ varied in wide ranges, while the other cladding parameters were either kept constant or had values close to each other. As a result of the experiments, it was found that the above structural characteristics of metal-fiber materials do not affect appreciably the values of the heat-exchange coefficient, which lie within the limits of experimental error.

The relationship between the heat-exchange intensity in boiling and the physical characteristics of the liquid was investigated in the fourth series of experiments on the same specimens, using water, acetone, and ethyl alchohol as coolants in the saturation pressure range $(0.5\text{-}0.98) \cdot 10^5$ Pa. Analysis of the experimental data indicates that the liquid characteristics exert a considerable effect on the heat exchange. The heat-exchange intensity in boiling on porous claddings under capillary transport conditions depends on the complex of the liquid's physical characteristics $\lambda_{li}^2/\nu_{li}\sigma T_{sat}$ [8], the heat of evaporation, and the vapor density.

The thermal contact resistance $R_{ct}$ between the porous structure and the heating surface affects substantially the evaporation process intensity under conditions of capillary liquid transport, as was demonstrated in [3]. Nevertheless, it is still assumed that the heat exchange intensity in boiling under these conditions does not depend on the quality of contact between the cladding and the surface. In order to check this proposition, a series of experiments was performed on specimens with sintered-on capillary-porous structures as well as specimens where this structure was pressed tightly onto the base-layer surface. The value of $R_{ct}$ was small in the first case, while it was considerable in the second, where it varied within the $(20\text{-}100) \cdot 10^{-5}$ m²·°K/W range, depending on the pressing force. The values of the

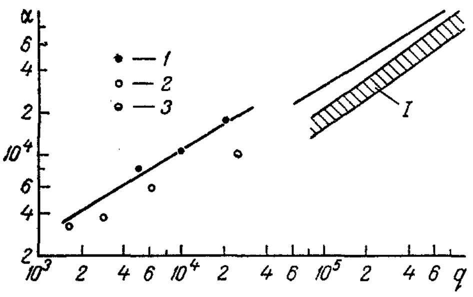


Fig. 4. Heat-exchange intensity in water boiling at a copper heating surface covered by porous, metal-fiber claddings under capillary transport conditions. Nickel-fiber specimens ($p_{sat} = 0.98 \cdot 10^5$ Pa): 1) $\Pi = 0.87$, $\delta = 2.5$ mm (our data); 2) 0.8 and 0.74 mm [6]; 3) 0.8 and 2.08 mm [7]; copper-fiber specimens ($p_{sat} = 0.1 \cdot 10^5$ Pa): 1) $\Pi \approx 0.4$, $\delta = 1.5$ mm, experiment and calculations [4]; the solid curves pertain to calculations based on Eq. (1). q, W/m².

heat exchange coefficient were much higher in boiling on specimens with sintered-on claddings than with pressed-on claddings by a factor of 1.2-1.5 in the range of low thermal flux densities ($q < 5 \cdot 10^4$ W/m²), and by a factor of 2-3 in the $q > 10 \cdot 10^4$ W/m² range. The boiling process, which was visible at surfaces with sintered-on claddings, could not be observed visually on specimens with the pressed-on structure. The water outflow was in this case provided along the base-layer surface.

These results show the importance of quality bonding of the porous cladding, achieved, for instance, by sintering the structure particles onto the heating surface. The unequal values of the thermal contact resistance between the capillary structure and the heating surface could be one reason for the often considerable discrepancies between the experimental data on the heat exchange in boiling provided by different authors.

The results of experimental investigations on the heat exchange intensity at surfaces with sintered-on, porous metal-fiber claddings in liquid boiling under capillary transport conditions are adequately approximated by the relationship

$$\alpha = kq^{0,6}\delta^m \lambda_f^{0,07}(r\rho_v)^{0,3}\left(\frac{\lambda_{li}^2}{\nu_{li}\sigma T_{sat}}\right)^{0,2}, \tag{1}$$

where $k = (9.43 \cdot 10^{-2}) \cdot (\sqrt{\lambda_m c_m \rho_m})^{0.4}$, and $m = 0.65$ for $0.4 \cdot 10^{-3} \leq \delta \leq 1.2 \cdot 10^{-3}$ m; $k = (0.31 \cdot 10^{-3}) \cdot (\sqrt{\lambda_m c_m \rho_m})^{0.4}$, and $m = -0.2$ for $1.2 \cdot 10^{-3} < \delta \leq 9 \cdot 10^{-3}$ m.

The coefficient k in (1) reflects the effect of the characteristics of the heating surface on the heat-exchange intensity. For instance, for a copper surface, $k = 6.43$ for $\delta \leq 1.2$ mm and $k = 21.16 \cdot 10^{-3}$ for $\delta > 1.2$ mm. The thermophysical and the physical characteristics of the heating surface material, the fibers, and the liquid in Eq. (1) are determined with respect to the saturation temperature.

Relationship (1) generalizes 95% of the experimental data with an error of ±25%; it holds in the range of the cladding characteristics given in Table 1 and the range of process parameters meeting the condition determining the boundary of boiling zone I according to [3]:

$$\Delta T < 4\sigma T_{sat}/r\rho_v D_{min}, \tag{2}$$

the validity of which is supported by an analysis of the experimental results. The recommendations given in [3] can be used for calculating the heat-exchange intensity in boiling zone II.

For boiling zone I, Fig. 4 provides a comparison between our theoretical and experimental data and the results obtained in [4, 6, 7], where porous, metal-fiber claddings were used. It is evident from the figure that the values of the heat-exchange coefficient calculated on the basis of (1) are in satisfactory agreement with the experimental data on fiber specimens made of different metals at both atmospheric and lower saturation pressures.

## NOTATION

Π, cladding porosity; D, pore diameter; δ, cladding thickness; λ, thermal conductivity coefficient; c, specific heat; ρ, density; ν, kinematic viscosity coefficient; σ, surface tension coefficient of the liquid; r, heat of evaporation; T, temperature; ΔT, temperature drop; q, thermal flux density; α, heat-exchange coefficient. Subscripts: min, minimum; f, frame; m, material; li, liquid; v, vapor; sat, saturation.

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# MOTION OF A NONLINEARLY VISCOPLASTIC FLUID JET ALONG A PLATE MOVING AT AN ANGLE TO THE HORIZON

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Stationary stabilized flow of a plane fluid jet along a moving inclined plane is considered.

Used extensively in the wood processing industry is the process of infusion application of paint and varnish coatings as follows. The articles pass under an apparatus forming a plane jet (curtain) of downward incident varnish (Fig. 1) [1].

The fundamental parameter of the process is the coating thickness which governs its protective-decorative property and cost.

At present, coatings are applied on horizontally moving articles, hence, their thickness is determined from the relationship $h = Q/u_p$.

A number of papers has recently appeared that indicate the expediency of moving the article at an angle to the horizon. The passage to the new infusion scheme requires the determination of the thickness of the jet of varnish material on the moving inclined plane.

To solve such a problem, the equation of the rheological state of the fluid must be given, to describe the rheological behavior of varnish materials. A number of empirical models has been proposed. Without analyzing their confidence, a solution of the problem has been obtained in this paper for all the models proposed. To this end, the Shul'man [2, 3] four-parameter rheological equation of state has been taken, which generalizes all models of varnish materials. This would permit not only relating the coating thickness to the technological and rheological parameters of the process, but also to clarify how the selection of the rheological equation of state influences the relations describing the process as well as how intensively must the rheological properties of the varnish materials be studied to describe their application by infusion.

## 1. FORMULATION OF THE PROBLEM

Let there be a jet of nonlinearly viscoplastic fluid moving along a plate. We assume the flow stationary and stabilized. The fluid flow rate per unit jet width is Q. In its turn the plate moves at a velocity $u_p$ at an angle $\alpha$ to the horizon. We direct the coordinate axes as shown in Fig. 1. We consider the angle $\alpha$ positive during upward motion of the plate and negative during downward motion.

In the case under consideration, the Shul'man rheological model will have the form

$$\tau = \operatorname{sign}\left(\frac{du}{dy}\right)|\tau|,$$

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