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OPTIMIZATION OF THE PARAMETERS OF A POROUS COATING UNDER CONDITIONS OF POOL BOILING OF PROPANE

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Results of an investigation of the influence of the parameters of a sintered porous copper coating on heat transfer under conditions of propane boiling are reported. The experiments were carried out within the ranges of specific heat fluxes of $q = 10^2\text{–}6.4 \cdot 10^4$ *W/m*^{2} *and of saturation vapor pressures of* $p_s = 0.48\text{–}1.08$ *MPa* ($T_s = 0\text{–}30^oC$)*. Optimum parameters of the porous coating were determined within the investigated saturation pressure range. A dimensionless equation is suggested for determination of the heat-transfer rate in propane boiling on sintered porous copper coatings.*

Introduction. Heat exchangers find wide use in various fields of technology: in power engineering, in the chemical, petroleum-processing, and food industries, in refrigeration and cryogenic technology, and in thermal engines and space technology. Therefore it is of great importance to develop and bring to an industrial level energy- and resource-saving technologies allowing the economical and rational use of energy and material resources. At present, active searches for environmentally safe and nontoxic heat-transfer agents capable of providing efficient heat transfer are underway. It is known that in their thermophysical properties the ozone-destroying Freons have hydrocarbon analogs (propane, propylene, butane, propane-butane mixtures) that possess a number of unique properties and serve as their candidates. Among the most promising hydrocarbons is propane, which in addition to good thermophysical characteristics possesses high dielectric properties and chemical compatibility with the majority of structural materials. Owing to these properties, propane can be widely used in refrigeration equipment, in evaporative submersible heat exchangers for cooling of microelectronics devices, and as a working fluid in heat pipes.

Experimental. Experiments were carried out on an experimental setup using the procedure of [1, 2]. The experimental specimens represented horizontal copper ∅ 20 × 1.75 mm tubes with a length of 100 mm, on the external surface of which a porous coating was sintered. The characteristics of the porous structures are given in Table 1. The porosity of the coatings amounted to 50–55% which corresponds to the optimum value for the highly heat-conducting structures according to the data of some authors [3, 4, et al.]. The heat-transfer coefficient was calculated by the formula adopted for a smooth tube:

$$\alpha = \frac{q}{T_w - T_s} . \tag{1}$$

The specific heat flux was calculated by the ratio of the supplied power, with allowance for heat loss, to the external surface area of a coating-free tube:

$$q = \frac{Q}{F_{sm}} . \tag{2}$$

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TABLE 1. Characteristics of the Investigated Coatings

Coating thickness $\delta_{\text{c.layer}}$, mm	Particle diameter d_p, μm	Mean particle size $\langle d_p \rangle$, μm	Mean hydraulic size of pores $\bar{d}_0$, μm	Capillary penetrability $k \cdot 10^{11}$, m^2
0.05–0.06	40–63	51.5	–	–
0.2			18.37	0.48
0.3				
0.4				
0.5				
0.3	63–100	81.5	24.48	0.802
0.4				
0.5				
0.6				
0.8				
0.4	100–160	130	35.4	1.553
0.5				
0.5	160–200	180	48.8	2.758

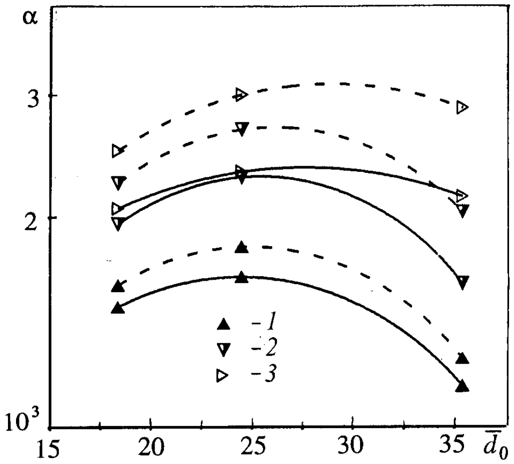

Fig. 1. Influence of the mean hydraulic size of pores on the heat-transfer rate for different heat fluxes (T_s = 20°C): solid line, $\delta_{\text{c.layer}}$ = 0.5 mm; dashed line, $\delta_{\text{c.layer}}$ = 0.4 mm; 1) q = 6 kW/m^2; 2) 15; 3) 64. α, W/(m^2·K); $\bar{d}_0$, μm.

Results and Discussion. An experimental study of the influence of the parameters of a porous coating on heat transfer with propane boiling was carried out on specimens with a sintered capillary-porous structure within the ranges of specific heat fluxes of q = 100–64,000 W/m^2 and of saturation pressures of p_s = 0.48–1.08 MPa (T_s = 0–30°C). It is known that the form of the boiling curves and the values of the heat-transfer coefficient substantially depend on the characteristics of the capillary-porous structure, namely, its geometric parameters, thermal conductivity of its skeleton, penetrability, wettability, and so on. One of the main parameters of the capillary structure is the mean hydraulic size of pores $\bar{d}_0$ characterizing the transport capability of a porous material upon its complete saturation with a working liquid. This quantity is the integral characteristic of the porous structure; it accounts for the type of coating and for the particle size and porosity.

In the investigated range of fractions, a nonmonotonous dependence of heat-transfer coefficients on the mean hydraulic size of pores was observed (Fig. 1).

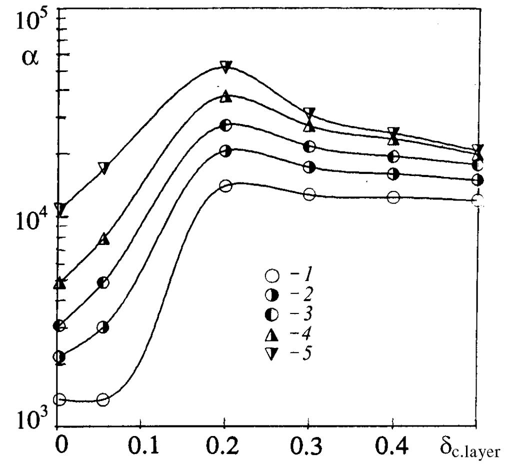

Fig. 2. Relation $\alpha = f(\delta_{\text{c.layer}})$ at different heat fluxes for the fraction with d_{p} = 40–63 μm, $T_{\text{s}} = 20^{\text{o}}$C: 1) q = 3 kW/m^2; 2) 6; 3) 10; 4) 20; 5) 64. α, W/(m^2·K); $\delta_{\text{c.layer}}$, mm.

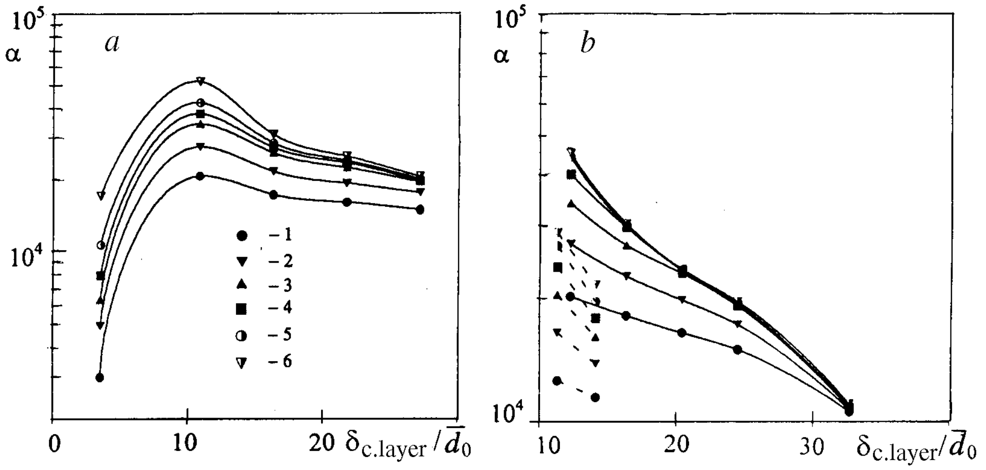

Fig. 3. Relation $\alpha = f(\delta_{\text{c.layer}}/\bar{d}_0)$ for different heat fluxes and fractions at $T_{\text{s}} = 20^{\text{o}}$C: a) d_{p} = 40–63 μm; b) solid line, d_{p} = 63–100 μm, dashed line, d_{p} = 100–160 μm; 1) q = 3 kW/m^2; 2) 6; 3) 10; 4) 15; 5) 20; 6) 64. α, W/(m^2·K).

As is seen from the figure, the optimum value of $\bar{d}_0$ corresponding to the highest heat-transfer coefficients at a fixed thickness of the coating depends on the specific heat flux. With increase in q the value of $d_{0\,\text{opt}}$ increases. However, in the investigated saturation pressure range the increase in the hydraulic size of pores by a value exceeding 30 μm exerts an adverse influence on the heat transfer, which is attributable to the decrease in the number of possible vaporization sites and to the violation of the conditions of thermodynamic and mechanical equilibrium of vapor nuclei. The decrease in $\bar{d}_0$ (less than 22 μm) also decreased the heat-transfer rate which is caused by deterioration of the conditions of removal of the vapor phase that are determined by the physical properties of the liquid and the capillary characteristics of the porous coating.

The thickness of the porous structure exerts a substantial influence on the heat-transfer rate. For the sintered capillary-porous structures consisting of fine particles, the main factor that specifies the form of the boiling curve and the heat-transfer rate is the change in the hydraulic resistance of vapor filtration from the evaporation zone to the external boundary of the coating. For such structures, the heat-transfer coefficient as a function of the thickness has a pronounced maximum at the fixed value of the heat flux (Fig. 2).

In this case, it is more convenient to represent experimental data as a function of the ratio of the thickness to the mean hydraulic size of pores $\delta_{\text{c.layer}}/\bar{d}_0$ rather than as a function of the porous coating thickness, which makes it possible to reveal the combined influence of the porous structure characteristics and to draw generalizing conclusions (Fig. 3).

Within the small-thickness range $\delta_{\text{c.layer}}/\bar{d}_0 < 11$, the release of vapor from the coating body occurs virtually freely and α increases with $\delta_{\text{c.layer}}$ owing to the formation of a more branched system of fine pores providing the liquid delivery to the heating surface due to capillary forces. At $\delta_{\text{c.layer}}/\bar{d}_0 = 11$–$12.5$, the heat-transfer coefficient attains its maximum values. Further growth of the coating thickness $\delta_{\text{c.layer}}/\bar{d}_0 > 12.5$ leads to a decrease in α due to an increase in the hydraulic resistance of vapor filtration.

Thus, on the basis of the experimental data obtained, the conclusion can be drawn that the dependence of the heat-transfer rate on the thickness of the capillary-porous coating and on the mean hydraulic size of pores is ambiguous. The influence of these parameters is closely interrelated, i.e., a change in the structure thickness $\delta_{\text{c.layer}}$ entails a change in the influence of $\bar{d}_0$ and vice versa. Consequently, in derivation of calculational relations, one must take into consideration the combined influence of these geometric characteristics of the porous coating on heat transfer. In this case, representation of experimental data in the form of the dependence $\alpha = f(\delta_{\text{c.layer}}/\bar{d}_0)$ accounting for the important geometric parameters of the capillary structure seems to be the most complete.

Generalization of the Results. In generalizing the experimental data on the rate of heat transfer with pool boiling of propane on sintered capillary-porous copper structures, use was made of the equation from [5], as the basic one, obtained for a smooth surface without account for the properties of the latter:

$$\mathrm{Nu} = C\,\mathrm{K}^m\,\mathrm{Pr}^n\,. \tag{3}$$

The number K is a specific criterion for different kinds of convective heat transfer: for free convection it is a Grashof or Archimedes number; for forced motion it is a Péclet or Reynolds number. For boiling heat transfer this number can be written according to [5] in the form

$$\mathrm{K} = \mathrm{Pe}\,\mathrm{Fo} = \frac{q}{r\rho_{\text{v}} d_0 f} = \frac{q}{r\rho_{\text{v}} w}\,, \tag{4}$$

where w is the growth rate of vapor bubbles characterizing the mean growth rate of the latter at a given point and the vapor efficiency of one vaporization site.

On the basis of experimental data, V. I. Tolubinskii [5] has obtained, in conformity with Eq. (3), a generalizing dependence that describes the known literature data on boiling of nonmetallic liquids:

$$\mathrm{Nu} = 75\,\mathrm{K}^{0.7}\,\mathrm{Pr}^{-0.2}\,, \tag{5}$$

or in expanded form

$$\frac{\alpha}{\lambda_{\text{liq}}}\sqrt{\frac{\sigma}{g\,(\rho_{\text{liq}} - \rho_{\text{v}})}} = 75\left(\frac{q}{r\rho_{\text{v}} w}\right)^{0.7}\left(\frac{\nu}{a}\right)^{-0.2}\,. \tag{6}$$

It is suggested to calculate w by the empirical relation [5]

$$w = 0.36\cdot 10^{-3}\,(p/p_{\text{cr}})^{-1.4}\,.$$

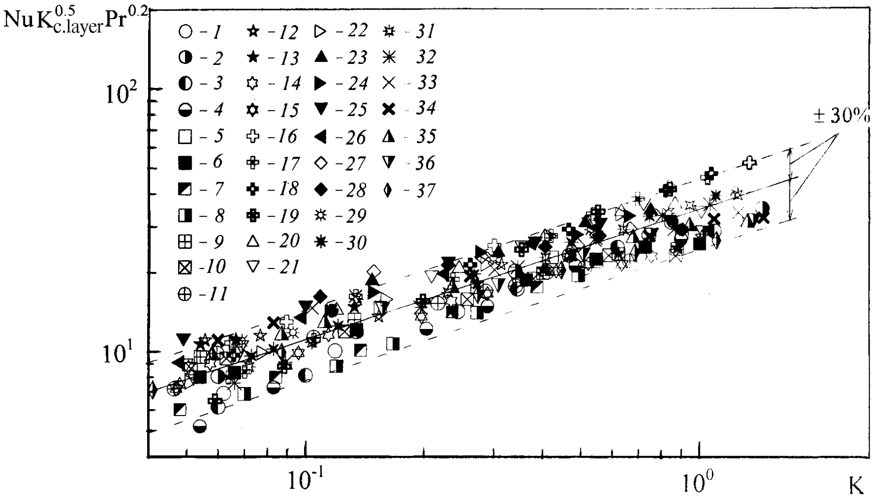

Fig. 4. Generalization of the experimental data on heat transfer under conditions of propane boiling on the surface with a sintered porous structure (see notation in Table 2).

TABLE 2. Parameters of the Investigated Porous Structures and the Experimental Conditions

No. of points in Fig. 4	Particle diameter d_p, μm	Coating thickness $\delta_{c.layer}$, mm	Saturation temperature T_s, °C
1, 2, 3, 4	40–63	0.2	20, 30, 10, 0
5, 6, 7, 8		0.3	30, 20, 10, 0
9, 10, 11		0.4	20, 10, 0
12, 13, 14, 15		0.5	30, 20, 10, 0
16, 17, 18, 19	63–100	0.3	30, 20, 10, 0
20, 21, 22		0.4	20, 10, 0
23, 24, 25, 26		0.5	30, 20, 10, 0
27, 28		0.6	20, 10
29, 30, 31, 32	100–160	0.4	30, 20, 10, 0
33, 34, 35, 36		0.5	30, 20, 10, 0
37	160–200	0.5	20

This equation, accounting for the internal characteristics of the process and unambiguously determining the vaporization rate, can be employed for derivation of a generalizing relation in the case of boiling on a porous surface.

As a coefficient accounting for the geometric characteristics of the capillary-porous structure, the following dimensionless quantity can be proposed for Eq. (3):

$$\mathrm{K_{c.layer}} = \frac{\delta_{\mathrm{c.layer}}}{d_0}\,. \tag{7}$$

Then, with account for the porous coating parameters, Eq. (3) can be written as

$$\mathrm{Nu} = C\,\mathrm{K}_{\mathrm{c.layer}}^{b}\,\mathrm{K}^{m}\,\mathrm{Pr}^{n}\,. \tag{8}$$

The generalization of experimental data by Eq. (8) within the ranges $\mathrm{K_{c.layer}} = 11–28$, $q = 1–30$ kW, and $p_s = 0.48–1.08$ MPa has yielded the following relation:

$$\mathrm{Nu} = 35\, \mathrm{K}_{\mathrm{c.layer}}^{-0.5}\, \mathrm{K}^{-0.5}\, \mathrm{Pr}^{-0.2} \tag{9}$$

or in expanded form

$$\frac{\alpha \bar{d}_0}{\lambda_{\mathrm{liq}}} = 35 \left(\frac{\delta_{\mathrm{c.layer}}}{\bar{d}_0}\right)^{-0.5} \left(\frac{q}{r\rho_{\mathrm{v}} w}\right)^{0.5} \left(\frac{\nu}{a}\right)^{-0.2} . \tag{10}$$

As is seen from Fig. 4, the suggested dimensionless relation allows determination of the heat transfer rate under conditions of pool boiling of propane on sintered porous copper coatings with an error permissible for design calculations.

Conclusions. Based on the experimental studies carried out, the dependence of the rate of heat transfer with propane boiling on sintered capillary-porous copper coatings on the dimensionless ratio $\delta_{\mathrm{c.layer}}/\bar{d}_0$, accounting for important geometric characteristics of the porous structure, has been revealed. The highest heat-transfer rate, up to a value tenfold higher than that for a smooth surface, was attained at $\delta_{\mathrm{c.layer}}/\bar{d}_0$ = 11–12.5. A dimensionless equation is suggested for determination of the heat-transfer rate for the case of pool boiling of propane on sintered porous copper coatings in wide ranges of heat fluxes and saturation pressures. The equation generalizes experimental results with an error of ±30%.

The results obtained can be used in designing evaporative heat exchangers for various fields of technology.

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NOTATION

a, thermal diffusivity; d_0, separation diameter of a vapor bubble; $\bar{d}_0$, mean hydraulic size of pores; *g*, free-fall acceleration; *f*, separation frequency of vapor bubbles; *F*, surface area; *p*, pressure; p_{cr} = 4.26 MPa, critical pressure; *Q*, heat flux; *q*, specific heat flux; *r*, heat of vaporization; *T*, temperature; α, heat-transfer coefficient; λ, thermal conductivity; ν, kinematic viscosity; $\delta_{\mathrm{c.layer}}$, thickness of the porous layer; ρ, medium density; σ, surface tension of the liquid; Nu, Nusselt number; Pr, Prandtl number; Pe, Péclet number; Fo, Fourier number; *b*, *m*, and *n*, exponents; *C*, constant. Subscripts: sm, smooth; c.layer, capillary layer; cr, critical; w, wall; liq, liquid; v, vapor; s, on the saturation line; opt, optimum; p, particle.

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