perature head; $K_l = c_{pl}(T_s - T_l)/r$, dimensionless subcooling; q, density of heat flux; r, heat of evaporation; F, area; G, mass flow rate per second; $Re_{lcr} = \rho_l u_l l_{cr}/\mu_l$, Reynolds number of the liquid phase; T, temperature; u, velocity; $\bar{u} = u_v/u_l$, ratio of the mean mass velocities of the phases (slip); z, axial coordinate; δ, thickness of the vapor film; λ, heat conductivity; μ, dynamic viscosity; ρ, density; σ, surface tension; φ, volumetric vapor content; x, mass vapor content. Subscripts: e, under conditions of natural convection; l, liquid; v, vapor; s, saturation; c, wall; 0, in the initial cross section; x, experimental value.

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EFFECT OF POROUS COATINGS ON HEAT EXCHANGE IN FILM BOILING

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The work concerns the investigation of heat exchange in film and transient boiling of water and Freon-113 on a surface with sintered porous metal coatings.

Film boiling is widely used in engineering. The heated surfaces on which film boiling occurs may have a porous coating that was specially applied or originated as a result of deposits. Oxide films and badly heated conducting coatings with different structures lead to increased values of q_{cr_2} and ΔT_{cr_2} [1-3] and of the heat transfer coefficient [4-6].

Zhukov et al. [5] investigated the effect of a porous layer of Al_2O_3 on heat transfer in film boiling of Freon-113 on a horizontal copper disk at atmospheric pressure. It was established that aluminum oxide applied by gas-flame spray coating causes the heat-transfer coefficient to increase to twice its value. Nikolaev and Tokalov [6] obtained data on the effect of a nickel coating 0.3 mm thick, applied electrolytically, on the heat exchange upon boiling of carbon dioxide. It was discovered that at a pressure of 71 bar, a porous layer in film boiling causes α to increase by a factor of 1.5. However, the effect of coatings on heat transfer in film boiling in the range of ΔT higher than ΔT_{cr_2} requires further study because, according to [1, 3], it does not manifest itself, and according to the data of [4-6] it exists.

The object of the present work is to investigate the effect of sintered coatings on the heat exchange in transient and film boiling. The data on heat transfer were obtained in cooling heated spheres coated with layers of various metals. According to [7], when the rate of change of the mean temperature of the section is less than 200°C/sec, the boiling may be regarded as a quasisteady-state process. This condition was met during the present work.

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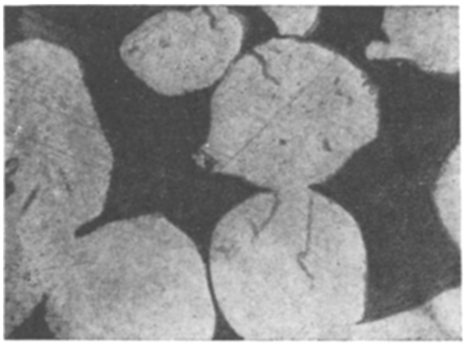

Fig. 1

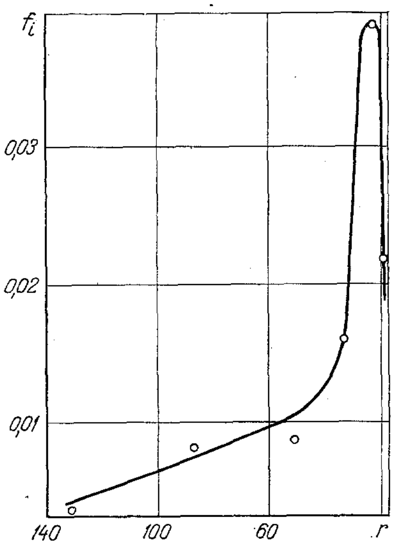

Fig. 2

Fig. 1. Section of a porous coating, ×200. Specimen No. 3.

Fig. 2. Differential size distribution of the relative pore volume. Specimen No. 1. f_i, 1/μm; r, μm.

The coatings, whose characteristics are presented in Table 1, were applied to a copper sphere with 20-mm diameter by the method of powder metallurgy. The surface and structure of the coatings were studied under a microscope. The photograph of a section of specimen No. 3, magnified 200×, is shown in Fig. 1. It can be seen that the disposition of the particles in the layer is random, its structure is inhomogeneous. The data on porosity, the differential and integral distribution of the pores were obtained by the method of mercury porometry.

Figure 2 shows the curve of differential distribution of the relative pore volume for specimen No. 1 which indicates that pores with size ∿25 μm predominate. The coefficient of thermal conductivity of the coating was measured by the method of regular regime of the first kind. From a comparison of the results for specimens Nos. 3 and 4 it may be concluded that the coefficient of thermal conductivity decreases with increasing porosity, and this is in agreement with the known physical notions.

The data on heat transfer were obtained with an installation described in [8]. The experiments were carried out with boiling distilled water and Freon-113 under conditions of free convection at atmospheric pressure. During the experiments the temperature of the sphere, of the working liquid, and of the vapor was measured by Chromel–Alumel thermocouples with 0.2-mm diameter of the thermoelectrodes; the emf of the thermocouples were recorded by a voltmeter-type F-30. The vapor pressure was checked by a reference manometer. The cooling curves of the spheres were recorded with the aid of a potentiometer KSP-4. The thermal flux conducted to the working liquid was determined by the formula

$$q = -\frac{Mc_p(T)}{F}\frac{dT}{d\tau} \approx -\frac{Mc_p(T)}{F}\frac{\Delta T}{\Delta\tau}.$$

TABLE 1. Characteristics of Coatings

No. of speci-men	Material of coating	Particle diam., mm	Thickness of coating, mm	Porosity, %	λ of coating in film boiling of, W/m·°C: water	λ of coating in film boiling of, W/m·°C: Freon-113	Temp. range of film boil-ing, °C
1	Copper, spray-coated	0,063	0,40	54	—	0,2	160—320
2	"	0,063	0,50	60	0,5	—	370—500
3	Bronze, tin spray-coated	0,2	0,60	64	0,4	—	500—600
4	The same	0,1	0,4	50	0,8	—	400—550
5	Nickel, electrolytic	0,075	0,25	68	—	—	80—300

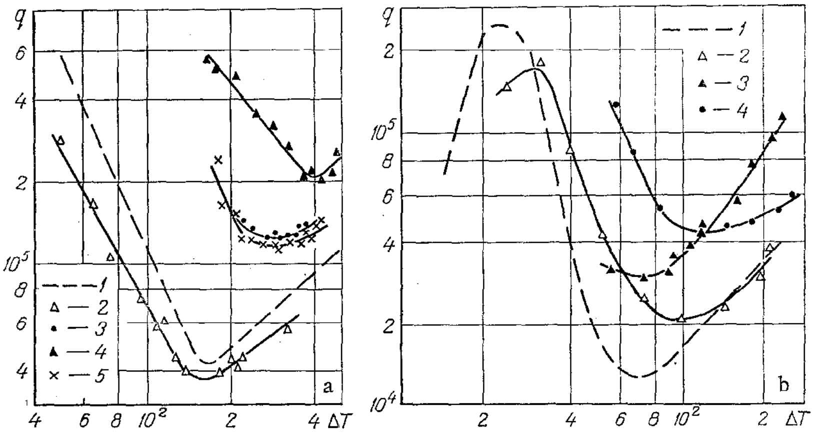

Fig. 3. Dependence of the thermal load on the difference of the temperature of the sphere and the saturation temperature of the liquid (a: water): 1) plate without coating [9]; 2) sphere without coating; 3) specimen No. 2; 4) No. 3; 5) No. 4; (b: Freon-113): 1) plate without coating [9]; 2) sphere without coating; 3) specimen No. 1; 4) No. 5. q, W/m²; ΔT, °C.

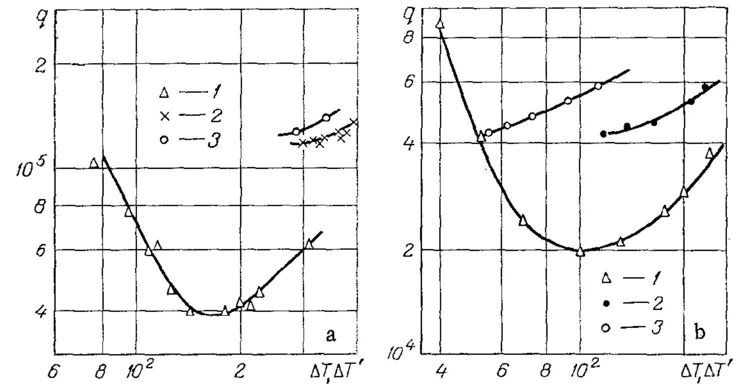

Fig. 4. Dependence of the thermal load on the difference between the surface temperature of the coating and the saturation temperature of the liquid (a: water): 1) sphere without coating; 2) specimen No. 4 in coordinates q–T; 3) specimen No. 4 in coordinates q–ΔT'; (b: Freon-113): 1) sphere without coating; 2) specimen No. 1 in coordinates q–ΔT; 3) specimen No. 1 in coordinates q–ΔT'. ΔT, ΔT', °C.

Figure 3 shows the obtained results concerning heat transfer. For the sake of comparison we also present the known data for an uncoated surface [9]. In the case of a coated surface, the value ΔT relates to the temperature of the base. The measurements of α for water (Fig. 3a) were carried out in the ranges q from $4 \cdot 10^4$ to $6 \cdot 10^5$ W/m² and ΔT from 50 to 500°C, and they include the transient as well as the film regimes of boiling. It can be seen that applying a porous layer leads to more intense heat exchange. For instance, in the case of specimen No. 4, the heat-transfer coefficient doubled. The value of q_{cr2} for specimens Nos. 2 and 4 increased three times, and of No. 3 five times. The data on heat transfer upon boiling of Freon-113 (Fig. 3b) were obtained in the ranges q from $2 \cdot 10^4$ to $2 \cdot 10^5$ W/m² and ΔT from 25 to 270°C, and they concern the transient as well as the film regimes. Like water, a porous coating intensifies heat exchange in film boiling. In the case of specimen No. 5, the heat-transfer coefficient increases by 1.5 times, and of No. 1 3 times. The value of q_{cr2} in specimens Nos. 5 and 1 increases by a factor of 2 and 1.5, respectively.

If the superheating of the wall is referred to the surface temperature of the coating, we obtain the dependence q(ΔT') shown in Fig. 4. In determining ΔT', we assumed linear temperature distribution across the thickness of the layers and used their characteristics given in Table 1. It can be seen from the figure that the heat-transfer coefficient for specimen No. 4 is twice, and of specimen No. 1, 2.5 times larger than in the case of an uncoated surface. The increase in the thermal resistance of specimens Nos. 4 and 1 amounts to 10 and 30%, respectively.

The noted effects of intensified heat exchange in film boiling may be caused by the influence of the thermophysical properties, thickness, porosity, and surface roughness of the coating. The investigated layers had a small coefficient of thermal conductivity, and this improved heat transfer. The coating may have a rougher surface than the uncoated surface, the roughness increasing with increasing particle size [10]. Increased surface roughness causes earlier cessation of film boiling; this can be seen from a comparison of the curves of boiling of specimens Nos. 3 and 4.

Thus the obtained data testify to a substantial intensification of heat exchange in film boiling with the aid of porous metal coatings. These results could be of interest to a number of branches of modern engineering.

NOTATION

α, heat-transfer coefficient, $W/m^2 \cdot {}^\circ C$; q, heat flux density, W/m^2; q_{cr2}, minimum critical thermal load, W/m^2; ΔT, difference between the temperature of the sphere and the saturation temperature of the liquid, °C; $\Delta T'$, difference between the surface temperature of the coating and the saturation temperature of the liquid, °C; ΔT_{cr2}, temperature head corresponding to q_{cr2}, °C; T_c, temperature of the sphere, °C; $dT_c/d\tau$, change in the temperature of the sphere with time, °C/sec; ΔT_c, $\Delta\tau$, temperature gradient and time interval, respectively, on the cooling curves of the sphere; F, surface area of the sphere, m^2; M, weight of the sphere, kg; c_p, specific heat capacity of the material of the sphere, $J/kg \cdot {}^\circ C$; λ, coefficient of thermal conductivity, $W/m \cdot {}^\circ C$; $f_i = \frac{\Delta \hat{V}_i}{\Delta r_i \sum_{i=1}^{n} \Delta V_i}$, probability density distribution, 1/μm; ΔV, relative pore volume; r, pore radius, μm.

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