numbers of the liquid; $Pr = \nu/\alpha$, Prandtl number; U, velocity of liquid; ν, kinematic viscosity of the liquid; $\delta^+ = U_*\delta/\nu$, $\delta_0^+ = U_*\delta_0/\nu$, dimensionless thickness of the film and viscous sublayer; $\eta_0 = \delta_0^+/\delta^+$; U_*, absolute viscosity; $Nu = \alpha\delta/\lambda$, local Nusselt number; λ, a, thermal conductivity and diffusivity of the liquid; α, local heat-transfer coefficient. Indices: w, wall; av, mean; t, turbulent; l, free surface of the liquid.

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EFFECT OF DEFECTS IN THE POROUS SURFACE ON THE THERMOPHYSICAL CHARACTERISTICS OF HEAT-PIPE WICKS

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UDC 536.423.1

Results are presented from a study of the effect of defects in the porous surface of a heat-pipe wick on the capillary head developed by the structure.

It is currently thought [1] that the presence of a defect (pores of a diameter greater than other pores) in the porous surface of a heat-pipe wick causes a significant deterioration in the performance of the pipe. This statement is assumed to apply to wicks of any geometry.

Let us examine a meniscus located in a pore of a capillary structure in the form of a perforated screen positioned with a gap relative to the heating surface of a heat pipe (Fig. 1). If the gap is large, a meniscus with a spherical surface (Fig. 1a) will be formed in the pore. As shown in [2], the minimum radius is determined as follows in the general case for a pore with curvilinear generatrices:

$$R_{s_1}^0 = \frac{a + R(1 - \sin\varphi^0)}{2\sin(\varphi^0 - \Theta)}. \tag{1}$$

The relation for determining φ^0 was presented in [2]. For a cylindrical pore, R = 0 and $\varphi^0 = \pi/2$.

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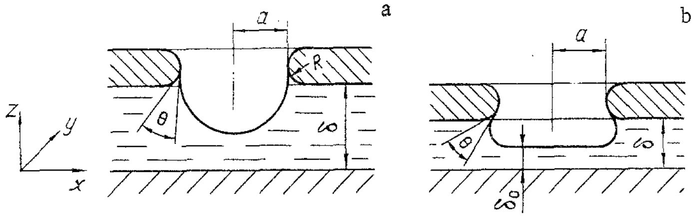

Fig. 1. Profile of the meniscus formed in a pore of a composite wick with different-size gaps δ.

With small gaps, the bottom part of the meniscus may approach the heating surface so closely that its profile is deformed, as shown in Fig. 1b [2]. Similar meniscus profiles are seen in thin-film units with longitudinal-wire-finned tubes [3] and in heated cylindrical capillary tubes [4]. In the case of a deformed meniscus profile, the minimum radius of its curvature is determined from the familiar relation

$$\frac{1}{R_d^0}=\frac{1}{R_y^0}+\frac{1}{R_z^0}. \tag{2}$$

Considering that the angle of contact between the top part of the meniscus and the surface of the screen is equal to Θ and the contact angle for the lower part is zero — since the meniscus is in contact with a thin film of the same liquid — Eq. (2) is easily transformed as follows:

$$\frac{1}{R_d^0}=\frac{1+\cos\Theta}{\delta-\delta_0}+\frac{1}{a+(\delta-\delta_0)\dfrac{1-\sin\Theta}{1+\cos\Theta}} \tag{3}$$

for a cylindrical pore and

$$\frac{1}{R_d^0}=\frac{1+\cos\Theta}{\delta-\delta_0}+\frac{1}{a+R+(\delta-\delta_0)\dfrac{1-\sin\Theta}{1+\cos\Theta}} \tag{4}$$

for a toroidal pore.

The thickness of the liquid film in the middle part of the meniscus δ_0 can be determined from the following considerations. It was shown in [5] that boiling is absent in capillary structures at high heat fluxes (i.e., under conditions when it is necessary to determine R_d^0). It follows from this that the liquid film on the bottom of the meniscus is so thin that boiling in this film is suppressed. The thickness of the liquid film in this case is determined by the relation from [6]

$$\delta_0=c\left(\frac{\sigma\lambda T_s}{r\rho''q}\right)^{0.5}. \tag{5}$$

The value of the coefficient c is different for different surface—liquid combinations. This is due to specific features of the physicochemical interaction of different liquids and heating-surface materials. For example, c ≈ 13 for the combinations copper—water, copper—butanol, and copper—heptane [6]. It should be noted that δ_0 is so small (particularly for organic coolants) at high heat fluxes that it can be ignored.

Generally speaking, the thin liquid film at the base of the meniscus should not be flat, as shown in Fig. 1b. Instead, it may have a certain curvature. However, due to the smallness of the pores, the difference in the thicknesses of the film in the center and at the periphery is very slight, and the film can be assumed flat without introducing a large error.

It can be seen from Fig. 1b that the minimum radius of curvature of the surface of a deformed meniscus depends mainly on the size of the gap between the screen and the heating surface. Under certain conditions, the R_d^0 of such a meniscus proves to be less than that of a meniscus with a purely spherical surface, and it develops a greater capillary head. Simultaneous solution of Eqs. (1) and (4) yielded an inequality determining the gap size at which the capillary head developed by a meniscus with a deformed surface is greater than that developed by a meniscus with a purely spherical **surface:**

$$\delta-\delta_0\leqslant\frac{(4ed+b^2)^{0.5}-b}{2e}, \tag{6}$$

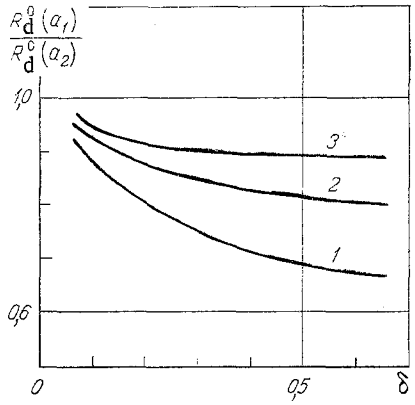

Fig. 2

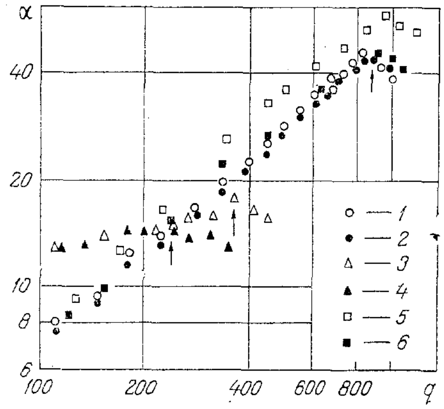

Fig. 3

Fig. 2. Relation between R_d^0 for pores of different size in relation to the gap size δ (mm): 1) a_1 = 0.25 mm, a_2 = 1 mm, Θ = 40°; 2) 0.25, 0.5 and 40; 3) 0.25, 0.5 and 0.

Fig. 3. Change in heat-transfer coefficient ($kW/m^2 \cdot K$) with an increase in heat flux (kW/m^2) in the evaporation of water from a wick with a pressure of 0.1 MPa (1-4 — perforated screen (a = 0.3 mm, P = 0.5) positioned with a gap relative to the heating surface; 5, 6 — brass grid No. 07 under GOST 3584-73): 1) 0.2-mm gap; 2) 0.2-mm gap, a = 0.75 mm in the center of the hole; 3) 0.75-mm gap; 4) 0.75-mm gap, a = 0.75 mm in the center of the hole; 5) tightly pressed grid; 6) grid, with hole in center with a = 0.85 mm, pressed tightly to the heating surface.

where

$$e = 2\,\frac{1-\sin\Theta}{1+\cos\Theta}\sin(\varphi^0-\Theta);$$

$$b = 2(a+R)\sin(\varphi^0-\Theta)-(2-\sin\Theta)[a+R(1-\sin\varphi^0)];$$

$$d = (a+R)(1+\cos\Theta)[a+R(1-\sin\varphi^0)].$$

Figure 2 shows calculated (from Eq. (3)) curves showing the character of the change in the relation between the minimum radii of the meniscuses of cylindrical pores of different geometry with a decrease in the gap between the heating surface and the perforated screen (with the assumption that δ_0 = 0). Two important conclusions can be made from analysis of these curves. First, for small values of the gap δ, the difference between the values of R_d^0 is insignificant even for pores with very different geometries. Second, the better the liquid wets the screen surface, the less the difference between the values of R_d^0 for pores of different sizes. Thus, the presence of a large pore (defective porous surface) in a composite wick has almost no effect on the value of R_d^0 when the gap between the screen and the heating surface is small. It therefore also has almost no effect on the magnitude of the capillary head developed by the wick, particularly for liquid metals and cryogenic liquids, for which Θ → 0. For example, for a composite wick made of a perforated plate with holes of 0.25 mm radius and positioned with a 0.1 mm gap relative to the heating surface (curve 2 in Fig. 2), the presence of a defective pore with a radius of 0.5 mm leads to a total increase of 4% in the minimum radius of the meniscus (4% reduction in the capillary head) for water (at atmospheric pressure) (here, we assume that the capillary head developed by the wick is determined by the geometry of the coarsest pore — the defect).

To verify the above arguments, we conducted tests on a unit simulating the evaporation zone of a heat pipe (the experimental set-up and method are given in [5]). In the course of investigating heat transfer in heat-pipe wicks, we established that the center of the test specimen dries up if the capillary head is insufficient to transport the liquid. The moment drying occurred was recorded not only visually, but from the change in the slope of the curve of the function α = f(q). This was also the basis of our tests. We measured the rate of heat transfer in the evaporation of water from a wick, which took the form of a perforated screen with cylindrical 0.6-mm-diameter holes and a surface porosity of 0.5. The

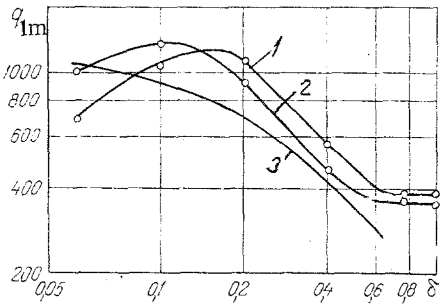

Fig. 4. Dependence of limiting heat flux (kW/m^2) in the evaporation of water from a composite wick on the size of the gap (mm) between the screen and the heating surface: 1, 2) perforated screen, a = 0.3 mm, P = 0.5 (p = 0.1 and 0.4 MPa, respectively); 3) brass grid No. 056 under GOST 3584-73, p = 0.4 MPa.

screen was positioned with gaps of 0.2 and 0.75 mm relative to the heating surface. The defect in the pore surface was modeled as follows. A hole 1.5 mm in diameter was cut in the center of the screen and we again determined α.

It can be seen from Fig. 3 that, with a gap of 0.2 mm, the curves of the change in α relative to q coincide, not only in terms of absolute values of the heat-transfer coefficient, but also with regard to the moment of beginning of drying of the wick center (denoted by arrows) and, hence, with regard to capillary head. With a gap of 0.75 mm, a composite wick with a large hole in the center begins to dry at considerably lower heat fluxes than the same wick without a surface defect. This is evidence that the former develops a lower capillary head.

The ratio of the heat flux at which drying of the center of a composite wick (Fig. 3) with a defective surface begins to the analogous heat flux for a nondefective wick is about 0.65 for a gap size of 9.75 mm. Here, the surface of the meniscus in a cylindrical pore with a = 0.3 mm is close to spherical, while its minimum radius, determined from Eq. (1), is 0.2 mm (for the calculations, we took a wetting angle of 40° from [7] for water with a pressure of 0.1 MPa). For a pore with a = 0.75 mm, the profile of the meniscus may be deformed. Here, the minimum radius, determined from Eq. (3), is about 0.3 mm. The ratio of these values is equal to 0.2/0.3 = 0.67 and is close to the above-cited ratio for the heat fluxes. This is convincing proof of the correctness of the representations made earlier in this article.

Similar results were obtained in experiments with grid-type wicks (Fig. 3).

At first glance, the composite wicks with a small gap (of the order of 0.1-0.2 mm) should have a serious shortcoming — high resistance to the flow of the coolant. Thus, the limiting heat fluxes that can be removed by such wicks should be lower than those for wicks with large gaps. However, the experiments indicate that the opposite is true (Fig. 4), thus confirming the promise of using heat pipes with wicks with a small gap between the screen and the heating surface.

The increase in capillary head with a decrease in gap size prevails over the increase in drag only up to certain values of δ: for example, up to thicknesses of the order of 0.1-0.15 mm in our tests (Fig. 4). At smaller gap sizes, the opposite pattern is seen and explains the decrease in limiting heat fluxes.

Calculations (with Eq. (6)) showed that the gap sizes at which the capillary head begins to increase agree well with the gap sizes at which the limiting heat fluxes begin to increase.

NOTATION

a, half the inside diameter of the pore; c, constant in Eq. (5); p, pressure; q, heat flux; q_{lm}, limiting heat flux; R, radius of curvature of edge of hole; R_s^o and R_d^o, minimum radii of curvature of profiles of meniscuses with spherical and deformed surfaces, respectively; R_y^o and R_z^o, minimum radius of meniscus in the planes x—y and x—z; r, heat of vaporization; T_s, saturation temperature; α, heat-transfer coefficient; δ, size of gap between screen and heating surface; δ_0, thickness of nonboiling liquid film; Θ, wetting angle; λ, thermal conductivity of liquid; ρ'', vapor density; σ, surface tension; P, surface porosity of wick.

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MIXING OF A FINE-GRAINED MATERIAL AND INTERNAL HEAT TRANSFER IN THE FURNACE OF A BOILER WITH A FLUIDIZED BED

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Results are presented from measurements and calculations of the temperature fields in the furnace of a boiler with a fluidized bed.

The use of a fluidized bed for the low-temperature combustion of fuels in the bed is promising compared to traditional methods of fuel combustion [1]. Introduction of this method in boiler technology is meeting several problems, some of which are related to inadequate knowledge of how to calculate temperature fields in the furnace boilers.

The empirical data in the literature [2, 3] on measuring the diffusion coefficient and diffusivity of a fluidized bed in the horizontal direction has been generalized for a free fluidized bed. There has not been enough study of problems of heat and mass transfer in fluidized beds constrained by tube bundles (boiler furnace analog), and the empirical formulas in [4, 5] require empirical verification in commercial-scale units. Thus, this work is devoted to study of the laws of heat and mass transfer in boiler furnaces with a fluidized bed.

The tests were conducted in a KPV-KS-5.7-14-180 experimental boiler with a fluidized-bed-equipped furnace. The experimental boiler was built at the heat and electric power plant of the scientific-industrial group of the I. I. Polzunov Central Scientific-Research, Planning, and Design Institute of Boilers and Turbines. Figure 1 shows the cross section of the boiler. The dimensions of the furnace in plan are 1.925 × 1.5 m. The upper zone of the bed, 380 mm from the cover, is constrained by the 28-mm-diameter tubes of the plant economizer. The side walls are shielded by the tubes. A more detailed description of the boiler can be found in [6].

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