NOTATION

b, width of corrugated strip; d, diameter; k, exponent; l, length; L, Labuntsov dimension; f) modulus; N) number of corrugations; Nu, Nusselt number; n, density of vapor generation centers; P, p, pressure; Q, heat flux; q, heat flux density; R, radius; Re*, modified Reynolds number; r, specific heat of vaporization; S, cross section; T, temperature; t, pitch; ω, velocity; α, heat-transfer coefficient; β, slope angle; δ, thickness; ζ, resistance coefficient; λ, thermal conductivity; ν, kinematic viscosity; ρ, density; σ, surface tension coefficient; τ, time; φ, vapor content. Subscripts: F, free volume; m, maximum; s, parameters on the saturation line; out, outflow; liq, wetted by liquid; ev, evaporation; cap, capillary; M, forces of gravity; c, column; w, wall; tr, transport; equiv, equivalent; ('), liquid; ("), vapor.

LITERATURE CITED

1. V. G. Zhigalov, A. L. Silinskii, and V. N. Cherkasov, "The desirability of using heat pipes in transistor power amplifiers," Nauch.-Tekh. Collection: Communication Technology, Ser. Tekh. Radiosvyazi, Issue No. 5 (1981), pp. 73-76.
2. A. V. Dvoryaninov, V. I. Kozlov, A. P. Osipov, and Yu. Yu. Sergeev, "Investigation of the characteristics of a low-temperature heat pipe with corrugated staggered wicks," Inzh.-Fiz. Zh., 37, No. 1, 13-19 (1979).
3. B. F. Aptekar' and Ya. M. Baum, "The influence of heat-transfer agent mass on the limiting heat transfer in a low-temperature heat pipe with a corrugated staggered wick," Tekh. Vys. Temp., 20, No. 1, 150-154 (1982).
4. G. F. Smirnov and B. A. Afanas'ev, "Experimental investigation of heat transfer with boiling in mesh structures of heat pipes," Vop. Radioelektron., Ser. TRTO, Issue No. 2, 22-27 (1979).
5. A. L. Koba, B. A. Afanas'ev, V. V. Erodnikov, and G. F. Smirnov, Investigation of Boiling of Liquids in Horizontal Planar Slots [in Russian], Moscow (1977). Division of VINITI, No. 1029-78.
6. G. F. Smirnov, "Calculation of the initial microlayer thickness in bubble boiling," Inzh. Fiz. Zh., 3, 503-508 (1975).
7. V. G. Zhigalov, E. M. Semyashkin, A. L. Silinskii, and V. N. Cherkasov, "Investigation of heat pipes with a corrugated capillary structure," Vopr. Radioelectron., Ser. TRTO, Issue No. 3, 19-24 (1983).

MACROSCOPIC BOUNDARY ANGLES OF WETTING OF SINTERED CAPILLARY STRUCTURES OF HEAT PIPES

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UDC 536.27.001

We measured the macroscopic boundary angles of wetting by water, acetone, and pentane of the capillary structures of antigravity heat pipes in the 293-363°K temperature range.

Most of the studies investigating the wetting of capillary structures of heat pipes have been devoted to metal-wire materials [1-3] and have practically no relation to sintered-powder capillary structures, which have also come to be rather widely used in heat pipes.

In order to estimate the wetting of capillary structures, investigators have used both conventional methods of studying compact (nonporous) materials [4, 5] and improved methods or methods specially designed for porous bodies [1, 2], in which account is taken of the variation of the structure of the material surface and of the influence of porosity on the wetting process. The boundary angle may be regarded as a fixed physicochemical characteristic only for systems which are in a state of thermodynamic equilibrium. For capillary structures of heat pipes it is difficult to regard the angle in this way because their

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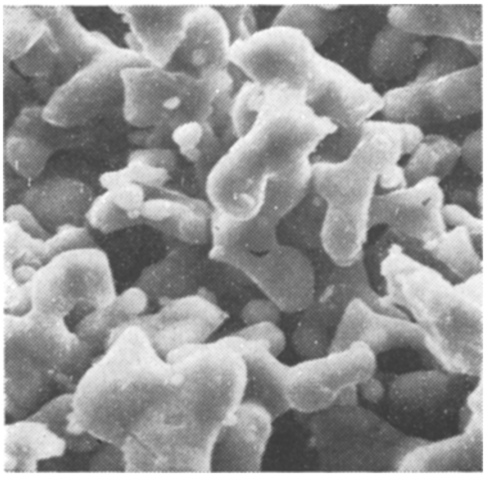

Fig. 1. Photomicrograph of the surface of a capillary structure made of powdered titanium, as seen under an electron scanning microscope (×1600).

surfaces are chemically and microgeometrically nonuniform. However, as was noted in [2], the conditions in a heat pipe are such that the wetting of a real capillary structure is no worse than for a model structure, and therefore the latter should be regarded as the worst possible case of wetting.

The experimentally determined quantities characterize the so-called macroscopic boundary angle Θ. This is an integral characteristic of the wetting of a large surface of a porous body and is different from the microscopic angle α, which appears when the microrelief of the wall surface is approached and there is "corrugation" of the wetting liquid [6]. The microscopic angle is observed if a characteristic dimension of an element of the liquid (the thickness of a layer or the radius of a droplet) is given by a quantity of the order of 10^{-7} m or less. In that case we must reckon with the fact that the specific free surface energy of the system depends not only on the nature of the adjacent phases but also by the dimension of a droplet. These effects have come to be known as capillary effects of the second kind [7], unlike the usual manifestations of capillarity, which are called effects of the first kind.

Capillary effects of the second kind change the shape of the surface in the immediate vicinity of the line of wetting. The profile of the surface changes the sign of its curvature and approaches the profile of the liquid film [8] formed on a solid surface as a result of the adsorption of liquid-phase molecules.

In the investigation of the properties of capillary structures and in the calculation of the capillary pressure and other characteristics of heat pipes, it is customary to use the macroscopic boundary angles Θ. However, this approach is not sufficiently rigorous. Evidently, after the capillary structures are soaked in the liquid, the boundary angles in each individual pore will be different from Θ. The finer the pore structure and the more fully developed and rough the surface of the particles of the capillary-structure skeleton, the more marked this difference will be. It may be assumed that in the case when the dimension of the nonuniformities of the wetted surface (e.g., the dimensions of the particles of the sintered powder) are commensurable with the radii of curvature of the vapor—liquid interface and are close in order of magnitude to 10^{-7} m, we will observe the formation of microboundary angles. Then the wetting will be nearly total, and the value of $\cos\Theta$ may be considered to be unity to a fairly high degree of accuracy.

However, it does not yet seem possible to make measurements of the boundary angles directly in the pores of the capillary structure. Therefore the authors were forced to retain the conventional approach in studying the wetting of porous materials and to determine the macroscopic boundary angles Θ.

In a previously published study [9] we obtained values of $\cos\Theta$ equal to 0.90 and 0.95 for water and acetone, respectively. We did not succeed in clearly demonstrating that the boundary angle depended on the porosity and the material of the capillary structure used in

TABLE 1. Main Structural Properties of the Porous Materials Investigated

Material	$\bar{r}_p$, μm	P_t, %	P_o, %	$K \cdot 10^{12}$, m^2	r_m, μm	$\bar{r}$, μm
Nickel	1,6	63,8	62,3	0,057	0,8	0,7
		61,3	60,5	0,027	0,7	0,6
		57,4	54,0	0,013	0,6	0,5
Titanium	15	60,0	60,0	0,553	3,1	2,9
		59,4	57,0	0,480	3,0	2,8
		56,8	55,2	0,405	2,7	2,6
	26	65,7	65,5	1,304	4,6	4,3
		63,2	61,8	1,025	4,0	3,9
		60,0	59,0	0,651	3,5	3,2

antigravity heat pipes [10, 11]. The purpose of our later investigations which led to this paper was to study the influence of temperature on the boundary angle in the 293-363°K range for water, acetone, and pentane.

The materials of the capillary structures were made of finely dispersed powdered titanium and nickel. The typical form of the surface of such structures is shown in Fig. 1. The variation in the properties of the capillary structures was achieved by varying the technological regimes of manufacture. In the analysis of the structure of the porous specimens obtained, we included a determination of the total and open porosities, the permeability to liquid, and the maximum and average dimensions of the pores by the method described in [12]. Table 1 shows the main structural characteristics of the capillary-structure specimens investigated.

For determining the boundary angles, we used the method of photofixation of the shadow image of the steady-state equilibrium meniscus when the liquid flowed onto a vertically positioned porous specimen. The observation and the photographing were carried out through an MBS-9 biological microscope. The chose method was tested in [9] and found to be completely successful. In order to vary the temperature, we added a heating unit and an automatic temperature-control unit set up on the basis of a KSP-4 potentiometer. The design scheme of the working chamber is similar to the one described in [5].

During manufacture and treatment, as is known, the investigated materials are contaminated by dust, powder particles, and films of oil and grease, which have an unfavorable effect on the wetting. Therefore the specimens were subjected to ultrasonic cleaning before the experiments. They were washed by means of a UZDN-1 disperser at an oscillation frequency of 19.5 kHz for 10 min, first in a mixture of propanol and acetone, then in distilled water. As was noted in [2], when the surface of the capillary structures is contaminated, the angle is practically independent of the structure of the wetted surface and the temperature is determined by the interaction of the coolant and the film of contamination. Perhaps this is the reason that in [9] we found the boundary angles to be unaffected by the structures (porosity, pore dimensions) of the specimen and by its chemical nature (nickel or titanium), since the specimens were not ultrasonically cleaned before the experiments.

After setting up the specimen, pouring in the coolant, and sealing the working chamber, we kept the specimen in the chamber for the period necessary for the coolant vapors to saturate the volume of the chamber (an average of 1.5-2 h), and then we took the first photographs at room temperature. The subsequent heating was carried out stepwise, raising the temperature by 5-10°K. The system of thermal regulation maintained the prescribed temperature within ±1°K. After concluding the experiments, we oxidized the specimens in air at a temperature of 620°K for 3 h, and then we repeated all the measurements on the oxidized materials.

The experimental results are shown in the graphs, plotting the boundary angle Θ against the temperature T. Figure 2 shows the experimental points indicating the influence of the temperature on the boundary angle of wetting of powdered-nickel capillary structures by pentane, acetone, and water. The porosity of the materials varied from 64% to 54%. The general character of the functional relation is the same for all coolants and indicates a decrease of the boundary angles as T increases.

Figures 3 and 4 show similar variations of the boundary angles of wetting of capillary structures made of powdered titanium of brands PTOM (56-60% porosity) and PTM (60-66% porosity),

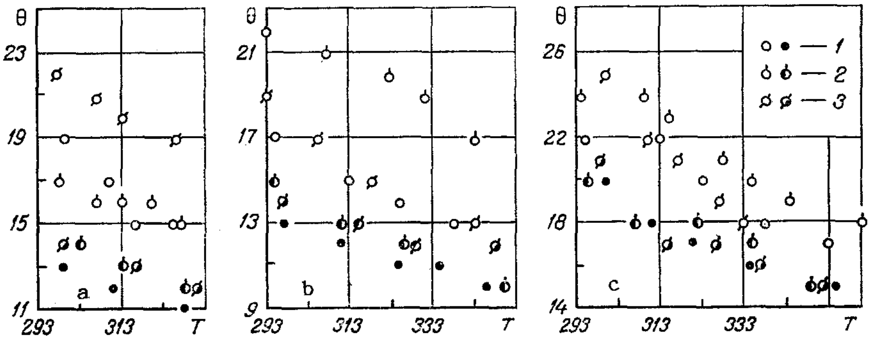

Fig. 2. Influence of temperature on the boundary angle of wetting of nickel capillary structures of various porosity values [1) P_t = 63.8%, 2) 61.3%, 3) 57.4%] by pentane (a), acetone (b), and water (c); the open circles represent the metal surface, while the solid circles represent the oxidized surface. θ, in degrees; T in °K.

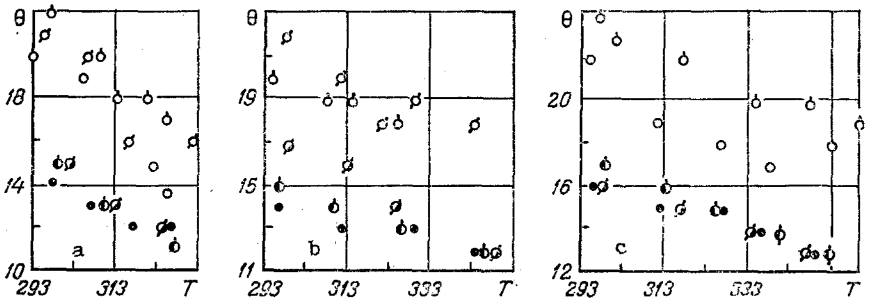

Fig. 3. Boundary angle of wetting by pentane (a), acetone (b), and water (c) of capillary structures made of PTOM powdered titanium as a function of temperature: 1) P_t = 60.0%, 2) 59.4%, 3) 56.7%. The notation is the same as in Fig. 2.

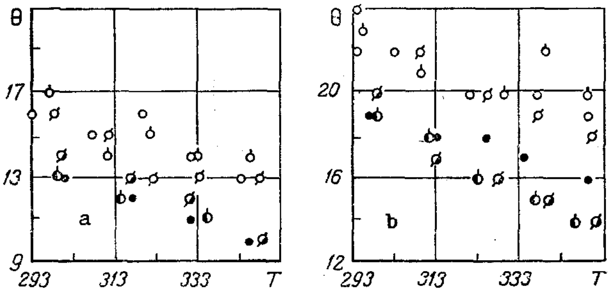

Fig. 4. Boundary angle of wetting by acetone (a) and water (b) of capillary structures made of PTM powdered titanium as a function of temperature: 1) P_t = 65.7%, 2) 63.2%, 3) 60.0%. The notation is the same as in Fig. 2.

respectively. An analysis of the graphs obtained shows that the influence of the temperature on the angle of wetting by the different coolants was the same for titanium capillary structures made of powders with different granulometric composition. Raising the temperature from room temperature by 50-60°K improves the wetting: for capillary structures made of PTOM powder the angle Θ changes from 21° to 16° for pentane, from 21° to 17° for acetone, and from 23° to 18° for water. Thus, the capillary structure is wetted about equally well by acetone and pentane, and less well by water.

Oxidation of the surface of the materials leads to an improvement in the wetting; the boundary angles decrease by 4-6°, which is in satisfactory agreement with the data of other authors [1, 2]. As can be seen from the figures, the experimental values for the oxidized capillary structures (solid circles) lie below those for materials with metallic surfaces. For comparison, we show the data of [2], in which Rybkin et al. investigated the wetting of powdered-titanium capillary structures (P_p = 26-35%, $\bar{r}$ = 5-13 μm) and powdered-nickel capillary structures (P_p = 27.5%, $\bar{r}$ = 1.5 μm). Upon heating, the boundary angle increases from 11° to 34° for titanium and from 20° to 45° for nickel. The reason for this, in those authors' opinion, is that when porous materials are wetted, the oxide film on the surface of the capillary structure is intensively dissolved as the temperature is increased, and consequently the wetting becomes poorer. At 330-340°K the oxide film is almost completely dissolved.

In the present investigation we did not observe any such phenomenon, and, as can be seen from the graphs, the wetting of the capillary structures improves as the temperature rises. The values obtained for Θ are in good agreement with the lowest values of the angle Θ found in [2] under the conditions preceding the start of dissolution of the oxide film.

The results indicate approximately equal wetting of porous materials made of powdered titanium and powdered nickel. Since the average dimension of a powdered-nickel particle is only 1/15 to 1/10 as large as the value for titanium, we can say, taking account of the favorable effect of roughness on wetting [4], that nickel capillary structures will be wetted less well than titanium ones for the same disperseness of the initial powders. This conclusion is fully consistent with the results of [2], in which the measured boundary angles for nickel structures are 8-9° larger than those for titanium structures.

From the results of the study it may be assumed that an increase in the porosity of a capillary structure leads to an improvement in its wetting. It can be seen from the figures that for capillary structures with lower porosity the angle Θ is larger, as a rule, than for more highly porous structures. However, this cannot be asserted with certainty because of the small range of variation in the porosity (only 5-6%) and the insufficient accuracy (within 2°) of the measurements.

Thus, the results obtained indicate that the capillary-structure materials used in antigravity heat pipes are satisfactorily wetted by all low-temperature coolants, owing to their high porosity, to the fine structure of the porous channels, and the extremely well-developed and rough shape of the pores and the powder particles. The average values of $\cos\Theta$ in the 293-363°K range for metallic surfaces of nickel and titanium are 0.93 in the case of water and 0.95 in the case of acetone. Oxidation of the material improves the wetting and increases $\cos\Theta$ to values of 0.95 and 0.98, respectively.

NOTATION

Θ, macroscopic boundary angle of wetting; α, microscopic boundary angle; T, temperature; P_t, total porosity; P_0, open porosity; K, permeability; $\bar{r}_p$, average dimension of powder particles; r_m, maximum pore radius, $\bar{r}$, average pore radius.

LITERATURE CITED

1. M. G. Semena, B. I. Rybkin, E. M. Sidorenko, et al., "Investigation of boundary angles of wetting of the wicks of low-temperature heat pipes," Inzh.-Fiz. Zh., 28, No. 2, 217-221 (1975).
2. B. I. Rybkin, M. G. Semena, E. M. Sidorenko, et al., "Investigation of boundary angles of wetting of capillary structures by low-temperature coolants," Prom. Teplotekh., 5, 42-47 (1983).
3. B. I. Rybkin, Yu. Yu. Sergeev, M. G. Semena, et al., "Investigation of the boundary angle of wetting of the mesh wicks of heat pipes by coolants," Inzh.-Fiz. Zh., 36, No. 4, 620-626 (1979).
4. A. D. Zimon, Adhesion of Liquids and Wetting [Russian translation], Khimiya, Moscow (1974).
5. V. I. Nizhenko, B. B. Bogatyrenko, A. G. Kostornov, et al., "Investigation of equilibrium boundary angles of the wetting by water, ethanol, and acetone of structural materials by low-temperature heat pipes," in: Thermophysical Research [in Russian], Vol. 2, Fizika Energeticheskii Inst., Obninsk (1980), pp. 90-97.
6. B. V. Deryagin, "Variation of the boundary angle as a function of the microrelief or the roughness of the wetted surface," Dokl. Akad. Nauk SSSR, 51, No. 5, 357-360 (1946).

7. L. M. Shcherbakov, "General theory of capillary effects of the second kind," in: Research in the Field of Surface Forces [in Russian], Izd. Akad. Nauk SSSR, Moscow (1961), pp. 28-37.
8. B. D. Summ and Yu. V. Goryunov, Physicochemical Foundations of Wetting and the Spreading of Liquids [in Russian], Khimiya, Moscow (1976), pp. 71-76.
9. G. V. Kuskov and Yu. F. Maidanik, "On the question of the boundary angles of wetting of the capillary structures of heat pipes," Submitted to the VINITI on June 8, 1983, No. 3781-83 Dep.
10. Yu. F. Gerasimov, G. T. Shchegolev, Yu. F. Maidanik, et al., "A low-temperature heat pipe with different channels for vapor and liquid," Teplofiz. Vys. Temp., 12, No. 5, 1131-1134 (1974).
11. Yu. F. Gerasimov, Yu. F. Maidanik, G. T. Shchegolev, et al., "Low-temperature heat pipe with different channels for vapor and liquid," Inzh.-Fiz. Zh., 28, No. 6, 957-960 (1975).
12. Yu. F. Maidanik and G. V. Kuskov, "Porous titanium materials for capillary structures of heat pipes," Poroshk. Metall., No. 1, 36-38 (1983).

MODIFIED LEUNG–GRIFFITHS EQUATION FOR DESCRIBING THE THERMODYNAMIC PROPERTIES OF A CO_2–Ne SOLUTION NEAR THE CRITICAL POINT OF CO_2 VAPORIZATION

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A scaling equation of state is proposed, allowing for the asymmetry of the actual liquids and their nonasymptotic behavior with greater distance from the critical point. Experimental data for CO_2–Ne solutions near the critical point of CO_2 vaporization are approximated with this equation.

Binary solutions near the critical points of vaporization of the pure solvent have a number of characteristic properties. Even at very low concentrations there is a region of temperatures and pressures at which molecules of the dissolved substance interact with each other so strongly that the solution becomes essentially nonideal. The compressibility of the system and the derivative of the concentration of the component with respect to its chemical potential increase strongly in the critical region, which leads to peculiarities of the kinetic properties such as diffusion and thermal conductivity (thermal diffusivity) and to an increase in fluctuations of concentration and density, while the partial molar volume of the solvent can even assume negative values [1]. The complexity of the description of critical phenomena in such solutions is due primarily to the existence of two strongly fluctuating order parameters, connected with the density and concentration. At the same time, the situation is simplified to a certain extent by the presence in this region of an additional small parameter — the concentration of the dissolved substance. The latter made it possible in [2, 3] to propose equations of state of the type of a Landau expansion in powers of the concentration and the departures of the temperature and density from the critical values for a pure solvent, as well as an equation of state based on the fluctuation theory of phase transitions of the second kind, from which the renormalization of the critical indices follows [4].

Several equations of state for the description of the thermodynamic properties of a binary solution in the region near the entire critical line of vaporization have also been proposed up to now. These are, primarily, the van der Waals equation of state [5] and the Leung–Griffiths [6] and Kiselev [7] equations.

The CO_2–Ne solution near the critical point of CO_2 was investigated for the further

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*Deceased.

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