INVESTIGATION OF THE EFFECTIVE THERMAL CONDUCTIVITY OF METAL-FIBER WICKS IN LOW-TEMPERATURE HEAT PIPES

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The heat-transfer coefficients in the condensation region of several low-temperature heat pipes with metal-fiber wicks were calculated.

The wicks of heat pipes may be made of the most variegated capillary-porous materials. Materials consisting of sintered monodisperse discrete fibers are among the most efficient wick materials. Metal-fiber wicks are free of the shortcomings of fabrics, metal screens, and powders, but still retain all their advantages: the great permeability of screens [1, 2], the good capillary absorption of fabrics [2, 3], and reliable contact with the envelope of the metal powders [4].

Previously, the skeletal thermal conductivity of wicks made of copper, nickel, stainless steel, and Nichrome fibers was experimentally determined by the steady-state technique [5]. Figure 1 shows the magnified (×75) structure of wicks made of sintered monodisperse discrete copper fibers with porosities of 90 and 96%. However, in the design and calculation of the operating characteristics of heat pipes the effective thermal conductivity of the wick is essential.

The present work contains the results of the investigations of the thermal conductivity of wicks saturated with the following liquids: technical-grade methyl and ethyl alcohol, acetone, and distilled water. The parameters of the samples made at the Institute of Materials Science, Academy of Sciences of the Ukrainian SSR are given in Table 1. The diameter of the monodisperse discrete fibers is d_f = 20-70 μ; the length, 3 or 10 mm. The standard material was lead (99.99%) with λ = 34.7 W/m•deg; for copper specimens of low porosity the standard material was aluminum (99.8%) with λ = 228.5 W/m•deg. The temperature range of the investigation was 16-35°C.

Before the experiment the investigated and the standard cylinder of 27.6 mm diameter and 30 mm length were placed between the cooler and the heater [6]. When the setup began to operate according to the stipulated conditions, measurements were carried out and the skeletal thermal conductivity was calculated by two methods: the absolute method and the relative method [5]. The values of λ_s, determined by the two methods, differed by 3-5%; i.e., the radial heat losses, which could distort the temperature field, were negligibly small. An exception were some wicks of extreme porosity (difference about 10%); this was caused by contact thermal resistance between the surface of the wick and the standard, and it was difficult to avoid it without deformation of the investigated specimen.

After the thermal conductivity of dry wicks had been determined, the inner space of the working section was evacuated to 10^{-3} mm Hg, the wick was saturated with working fluid, and the values needed for calculating the effective thermal conductivity by the absolute and the relative methods were measured. The difference in λ_{ef}, calculated by the two methods, was smaller than in the determination of λ_s because the thermal contact resistance between the surfaces of the specimen and the standard, even in highly porous wicks, was very small.

For investigating the effective thermal conductivity of wicks saturated with deaerated distilled water the specimens were oxidized [7]. It was found that the skeletal and effective thermal conductivities of both oxidized and nonoxidized wicks were equal. The degree

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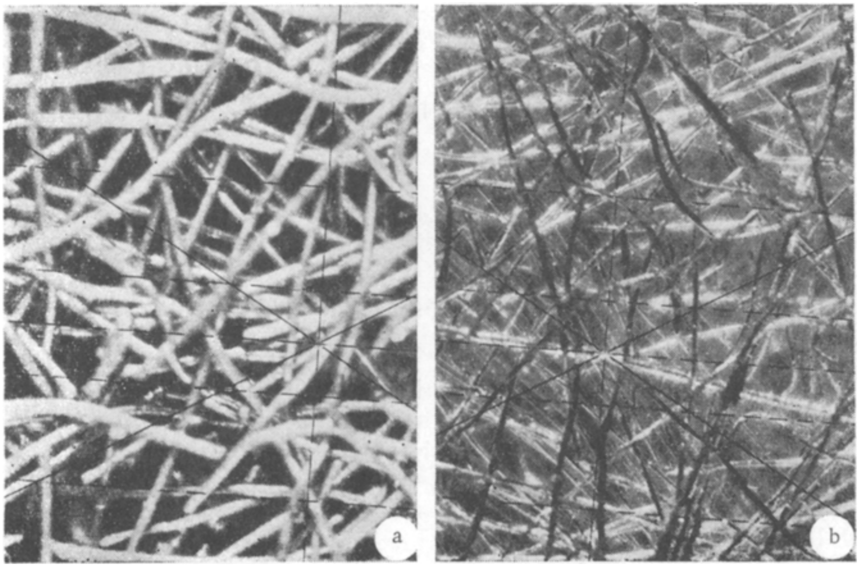

Fig. 1. Structure of metal-fiber wicks in the plane normal to the shaping force (×75): a) $d_f = 40\ \mu$, $l_f = 3$ mm, $\Pi = 90\%$; b) $d_f = 20\ \mu$, $l_f = 3$ mm, $\Pi = 96\%$.

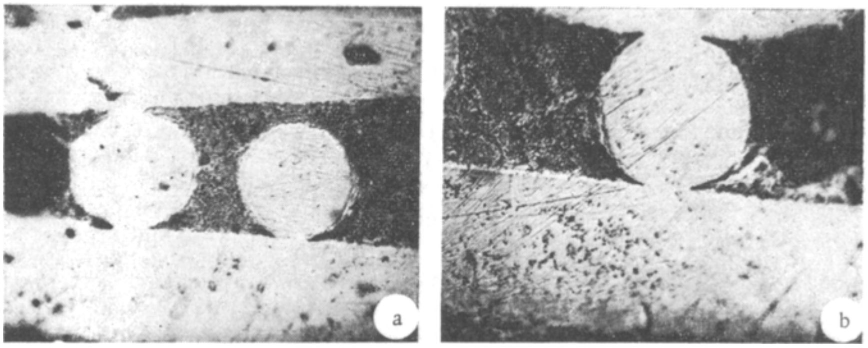

Fig. 2. Structure of metal-fiber wicks in the plane parallel to the shaping force: a) magnification ×400; b) ×500.

of saturation of the wicks with liquid was 94-96%, except for the specimens of very low porosity (Π = 10-20%). Since the measuring range of the temperatures was narrow (16-25°C) and the maximum temperature of the investigated specimens did not exceed 25°C, the natural convection of liquid in the pores of the wicks was of no consequence.

Although the determination of the thermal conductivity of wicks by the flat-layer method entailed a large error (8-37%), it nevertheless made it possible to establish that the thickness of the specimens does not affect their effective thermal conductivity. The mean value of λ_{ef} of the investigated specimens of different thicknesses but with equal porosity and fiber diameter and saturated with distilled water was close to the corresponding λ_{ef} in Table 1. The porosity of the wicks used in investigations by the flat-layer method was 60, 70, 80, and 90%, respectively; the thickness, 2, 5, and 10 mm; the diameter of the copper fibers, 20, 40, and 70 μ; and the length, 3 mm. The large error in the determination of λ_{ef} was here caused by the shortcomings of the flat-layer method (small thickness of the specimens and correspondingly small temperature gradients in the investigated specimens).

A special feature of the materials made of monodisperse discrete fibers is that the particles are not equiaxial and therefore the conductivity properties are anisotropic because in such a structure the fibers arrange themselves with their longer section in the plane perpendicular to the shaping force (Fig. 1a, b) and their short section in the plane parallel to the shaping force (the circular sections of the fibers are shown in Fig. 2a). The thermal and electrical conductivities of metal-fiber structures longitudinally and transversely may differ by several units [8, 9]. In the present work the effective thermal conductivity of the wicks was determined in the plane parallel to the shaping force; i.e., the heat transfer

TABLE 1. Effective Thermal Conductivity of Metal-Fiber Wicks

Wick material	d_f, μ	Π, %	λ_{ef}, W/m·deg alcoh.	λ_{ef}, W/m·deg H_2O	Error, %
Copper	20	21,1	240	240	±3
		35,2	139	139	±3
		50,0	66,5	66,5	±5
		66,4	21,0	21,8	±5
		79,8	8,17	8,45	±5
		89,5	3,86	4,42	±7
		96,1	2,85	3,23	±10
	40	19,9	201	201	±3
		35,6	98	98	±5
		49,7	40	40	±5
		64,9	14,3	14,7	±7
		79,9	5,3	5,72	±7
		88,9	3,34	3,85	±10
	70	19,8	174	174	±3
		36,0	72,1	72,1	±5
		49,8	27,6	27,6	±5
		65,1	10,7	11,1	±5
		78,3	4,9	5,3	±7

Wick material	d_f, μ	Π, %	λ_{ef}, W/m·deg alcoh.	λ_{ef}, W/m·deg H_2O	Error, %
Copper	70*	21,2	200	200	±3
		34,1	117	117	±3
		50,3	47,8	47,8	±5
		65,4	16,4	17,0	±5
		80,2	6,36	6,7	±5
Steel 1Kh18N	30	35,1	6,05	6,55	±5
		66,0	1,39	2,16	±5
		80,5	0,62	1,25	±5
Nickel	50	34,4	26,5	26,5	±5
		65,5	4,1	4,6	±5
		80,6	2,02	2,61	±5
Nichrome Kh20N80	50	10,6	10,4	10,4	±3
		20,6	8,55	8,9	±5
		35,4	5,77	6,21	±5
		50,3	3,22	3,92	±5
		65,5	1,51	2,37	±5
		80,3	0,68	1,35	±5

*In this case l_f = 10 mm.

TABLE 2. Effective Thermal Conductivity of Metal Wicks with Different Structures

Porous structure	Wick material	Fiber or powder particle diam., μ	Porosity (%) or cell size (mesh, mm)	λ_{ef}, W/m·deg	Reference
Fibrous	Nickel	16	66,4%	9,53	
		16	84,2%	3,7	
		16	89,8%	2,86	[8]
	Copper	43	68,8%	33,2	
		43	81,8%	19,4	
Fibrous	St. steel		58%	9,6	
			80%	3,27	
			89%	2,46	[11]
	Nickel		61%	26,3	
			82%	5,5	
	Copper		59%	78,5	
Powdery		81	37,4%	2,69	[4]

Porous structure	Wick material	Fiber or powder particle diam., μ	Porosity (%) or cell size (mesh, mm)	λ_{ef}, W/m·deg	Reference
Powdery	Bronze	130	40,1%	2,64	[4]
		180	44,0%	2,93	
		260	42,3%	2,97	
Screen-like	St. steel	35	325 mesh	2,08	
		35	325 mesh	1,3	
		76	130 mesh	1,12	
	Bronze	35	325 mesh	1,75	[12]
Fibrous	Nickel		80%	2,34	
Screen-like	St. steel		0,14 mm	0,935	[13]
			0,4 mm	0,837	
			1,8 mm	0,655	

was accomplished across the fibers (in Fig. 2b the direction from the top downward). Such, in particular, is the direction of the heat flux in the heating and condensation regions of a heat pipe with a metal-fiber wick.

The effective thermal conductivities of wicks made from copper, stainless steel, nickel, and Nichrome fibers and determined by the steady-state comparative method, as well as the error of the experimental results, are given in Table 1. An analysis of Table 1 shows that λ_{ef} is most affected by the porosity of the wicks. A decrease in Π causes an abrupt increase in the thermal conductivity of the wicks and, in the final analysis, a drop in the thermal resistance of the entire heat pipe, but at the same time the hydrodynamic resistance of the wick increases [1]. Therefore, the optimum design parameters of a wick in each actual case of operation of the heat pipe have to be selected by simultaneously considering its hydrodynamic and thermophysical characteristics.

The material of the fibers also has a substantial effect on the effective thermal conductivity of the wicks. For instance, the λ_{ef} of 40-μ copper fibers (Π = 80%) saturated with alcohol is 2.6 times greater than the thermal conductivity of nickel fibers and 8.5 times greater than that of steel wires with the same porosity. It is therefore better to use copper

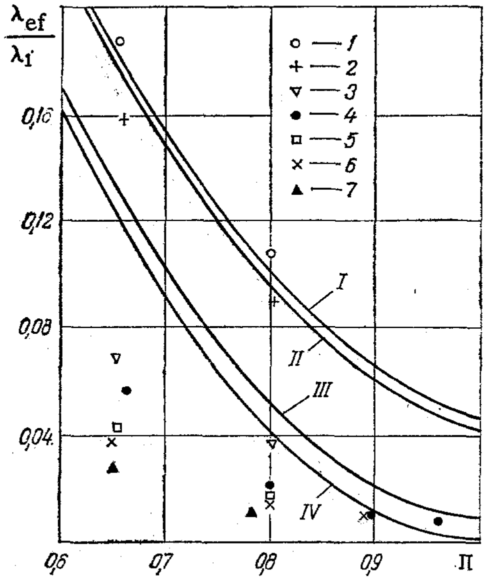

Fig. 3. Comparison of the effective thermal conductivity of water-saturated metal-fiber wicks with the calculated values. Experimental data: 1) Nichrome (d_f = 50 μ, l_f = 3 mm); 2) stainless steel (d_f = 30 μ, l_f = 3 mm); 3) nickel (d_f = 50 μ, l_f = 3 mm); 4) copper (d_f = 20 μ, l_f = 3 mm); 5) copper (d_f = 70 μ, l_f = 10 mm); 6) copper (d_f = 40 μ, l_f = 3 mm); 7) copper (d_f = 70 μ, l_f = 3 mm). Curves calculated by Eq. (1): I) for Nichrome (λ_1 = 12.5 W/m•deg); II) for stainless steel (λ_1 = 13.7 W/m•deg); III) for nickel (λ_1 = 66 W/m•deg); IV) for copper (λ_1 = 395 W/m•deg).

fibers in low-temperature heat pipes, all the more so since copper is more compatible with such coolants as acetone, ethyl alcohol, methyl alcohol, and water than is stainless steel [10].

The effective thermal conductivity of wicks also depends on the dimensions of the fibers. Longer fibers of smaller diameter have higher thermal conductivity. For instance, λ_{ef} of 20-μ copper fibers (Π = 80%, l_f = 3 mm), saturated with water, is approximately twice as great as that of 70-μ fibers (Π = 80%, l_f = 3 mm), and the thermal conductivity of wicks with d_f = 70 μ (Π = 80%, l_f = 10 mm) is 1.5 times greater than λ_{ef} for d_f = 70 μ (Π = 80%, l_f = 3 mm).

The type of coolant was found to have a negligible effect on the thermal conductivity of wicks. The differences in the thermal conductivities of wicks saturated with ethyl alcohol, methyl alcohol, and acetone lie within the measuring error. The λ_{ef} values of wicks saturated with alcohols or water are also close to each other. Only in the region close to extreme porosity values is λ_{ef} for water (λ_2 = 0.602 W/m•deg) higher than for alcohol (λ_2 = 0.179 W/m•deg), especially in wicks of stainless steel or Nichrome; this is due to their low skeletal thermal conductivity, which is close to the thermal conductivity of the coolants.

The effective thermal conductivity of metal-fiber wicks with Π ≤ 50% (for copper fibers Π ≤ 65%) is practically the same as the skeletal thermal conductivity. Saturation of wicks of a porosity of 65-96% with working fluid increases their thermal conductivity 1.1-4 times. For instance, the skeletal thermal conductivity of wicks of steel fibers with Π = 80.5% is 0.3 W/m•deg; the effective thermal conductivity of these same wicks when saturated with ethyl alcohol is 0.62; when saturated with water, 1.25 W/m•deg.

Table 2 contains the effective thermal conductivities of water-saturated metal wicks with different structures. The surface porosity of screens of 325 and 130 mesh is approximately 50 and 60%, respectively, and the surface porosity of screens with 0.14-1.8 mm clear mesh size is approximately 40-65%. A comparison of the effective thermal conductivity of metal-fiber wicks (Table 1) with the results of other works is difficult because the latter lack data on the length and diameters of the fibers [11, 12], the thermal conductivity of the

TABLE 3. Comparison of Experimental and Calculated Values of the Heat-Transfer Coefficients in the Condensation Region

Π, %	$\bar{\alpha}_s^{exp}$, W/m²·deg	$\bar{\alpha}_s^{c}$, W/m²·deg	Π, %	$\bar{\alpha}_s^{exp}$, W/m²·deg	$\bar{\alpha}_s^{c}$, W/m²·deg
93	2300	2500	88	3600	3800
90	1500	1300	88	4300	3900
90	2400	2000	84	4000	4650

fiber material [8], and the manufacturing conditions of the wicks. A different direction of the heat flux (heat transfer along the fibers) also makes a comparison with the results of [14] difficult.

An analysis of numerous models of thermal conductivity in porous materials showed that the model of an ordered fibrous structure, proposed in [5], is closest to the actual structure of wicks from discrete monodisperse fibers, which is also confirmed by Figs. 1 and 2. The effective thermal conductivity of fibrous materials of ordered structure is

$$\lambda_{ef} = \lambda_1 \left[\Pi^2 \nu + (1-\Pi)^2 + \frac{4\nu\Pi(1-\Pi)}{1+\nu} \right]. \tag{1}$$

The results of [5] show that such a model describes qualitatively faithfully the dependence of the thermal conductivity of dry metal-fiber wicks on the porosity. The discrepancy between the experimental results and the calculation by Eq. (1) was ascribed by the authors to the idealization of contact phenomena of the process of thermal conduction in fibrous systems. Equation (1) is derived by the analysis of thermal resistances which do not include thermal contact resistance; i.e., the contact area is taken as equal to the cross-sectional area of the fiber [15, 16]. This is obviously correct only for metal-fiber structures of low porosity where the data on the skeletal thermal conductivity of the wicks coincide much better with the calculation, but at $\Pi > 30\%$ the discrepancy is considerable.

The experimental investigation of the effective thermal conductivity of metal-fiber wicks confirmed the conclusions concerning the effect of the dimensions of the contact areas on the thermal conductivity across the fibers. In Fig. 3, in the porosity range that is of practical interest in regard to wicks of heat pipes, a comparison is given of λ_{ef}/λ_1 of sintered water-saturated copper, nickel, stainless steel, and Nichrome fibers with the calculation by Eq. (1). It can be seen from the figure that the effective thermal conductivity of the stainless steel and Nichrome wicks practically coincided with the calculated value, particularly in that range (Π = 60-80%) in which the discrepancy between λ_s and the calculation was greatest (1.5-2 times).

Because of the low skeletal thermal conductivity of stainless steel and Nichrome fibers, which is 0.3-0.8 W/m•deg (not only due to the low thermal conductivity of the material of the fibers but also due to the effect of the thermal resistance of the contacts), saturation of the wicks with a liquid "improves" the contact. The heat flux from the upper to the central fiber and from the central to the lower fiber (Fig. 2b) is transmitted in the near-contact zone not only through the contact area, but also through the liquid in the gap. The thermal conductivity of ordered fibrous structures with perfect contacts is well described by Eq.(1), and therefore the experimental results agree with the calculation. Naturally, the thermal conductivities of nickel and, especially, copper wicks differ from the calculated values (Fig. 3) because their skeletal thermal conductivities in this range of porosities are high (λ_s = 3-20 W/m•deg) and the heat transfer through the liquid in the gap (λ_2 = 0.2-0.6 W/m•deg) is very small compared with the heat flux through the contact area.

One of the stages of designing heat pipes is the calculation of their thermal resistance. The main contribution to the thermal resistance of low-temperature heat pipes comes usually from the condensation region. Table 3 contains a comparison of the experimental and the calculated values of the heat-transfer coefficients in the condensation region of some heat pipes (the calculation being carried out according to the known equivalent thickness of the wick and the coefficients of effective thermal conductivity). The material for the wicks of heat pipes was oxidized copper fibers of 20 and 40 μ diameter and 3 mm length. The diameters of the copper jackets of the heat pipes were 6-20 mm; the length, 250-500 mm; and the thickness of the wicks, 1-2 mm. The coolant was water. The discrepancy between the coefficient of thermal conductivity obtained experimentally ($\bar{\alpha}_s^{exp}$) and calculated using the respective work ($\bar{\alpha}_s^c$) is about 16%.

Similarly, the data on effective thermal conductivity can also be used for calculating the heat-transfer coefficients in the heating region, but only when the heat pipes (with fully saturated wicks) operate in the evaporation regime. The investigated heat pipes with metal-fiber wicks operated in the evaporation regime in the density range of the supplied heat flux of up to approximately 0.5-1 W/cm².

NOTATION

d_f, l_f, diameter and length of monodispersed discrete fibers; Π, porosity; λ_s, λ_{ef}, skeletal and effective thermal conductivities of wicks; λ_1, thermal conductivity of fiber material; λ_2, thermal conductivity of a coolant; $\bar{\alpha}_s^{exp}$, $\bar{\alpha}_s^c$, experimental and calculated coefficients of heat transfer in the condensation region; $\nu = \lambda_2 \lambda_1$, ratio of liquid thermal conductivity to fiber thermal conductivity.

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