SKELETAL THERMAL CONDUCTIVITY OF FIBER-METAL HEAT-PIPE WICKS

M. G. Semena, A. G. Kostornov,
V. K. Zaripov, A. L. Moroz,
and M. S. Shevchuk

UDC 536.2.022

The steady-state comparison method is used to determine the skeletal thermal conductivity of fiber-metal heat-pipe wicks.

Heat pipes have several unique properties – effective heat transfer with very small differences in temperature between the heat source and sink, the ability to transform the heat flux density, and the ability to stabilize the temperature of thermally stressed surfaces. These properties, combined with compactness, autonomy, and high reliability, account for the wide application of heat pipes in various branches of science and technology. These advantages, however, cannot always be realized owing mainly to the defective nature of the wicks, which are the main structural component in heat pipes. A wick is a capillary-porous structure in which movement, evaporation, and condensation of the working fluid take place.

The most common wicks are made of metal screen or textile fabrics, which are attached in some way to the heat-pipe wall. The main deficiency of such wicks is the high thermal resistance of the wick itself and the wick–wall contact. In addition, during the operation of the heat pipe, the repeated thermal expansion of the wick causes it to come apart, break away from the wall in places, and become incapable of transporting the fluid. A significant drawback of metal screen and fabric wicks is their unsuitability for operation of heat pipes against the force of gravity.

Wicks based on powdered materials are sintered to the walls and are free of most of the above deficiencies . Powder structures, however, have low permeability, due to their low maximum porisity (50-60%), the presence of blind pores, and also due to the low capillary absorption characteristics which result from the presence of closed cavities.

Wicks sintered from monodisperse metal fibers are superior in their properties – high permeability [owing to the practically unlimited porosity (up to 98%) and complete absence of blind pores], good capillary absorption, and high thermal conductivity – to screen and powder wicks [1]. The technology of fabrication of fiber-metal wicks allows the construction of heat pipes of any geometry with prescribed and fixed working parameters. The calculation and design of heat pipes with fiber-metal wicks require a knowledge of the thermophysical characteristics of a capillary-porous structure, which have been poorly investigated so far.

In [2] the thermal conductivity of wicks of sintered nickel and copper fibers was determined. The experimental results were correlated by several empirical equations, which the authors recommend only for copper fibers of diameter 43 μ and nickel fibers of diameter 16 μ in a narrow range of porosity ($0.65 \leq \Pi < 1$).

TABLE 1. Values of Real Roots of Equation in [7]

Π	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9
λ_s/λ_1	0,86	0,72	0,59	0,47	0,36	0,27	0,18	0,11	0,05

Kiev Polytechnic Institute. Institute of Materials Research, Academy of Sciences of the Ukrainian SSR, Kiev. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 31, No. 4, pp. 581-586, October, 1976. Original article submitted July 23, 1975.

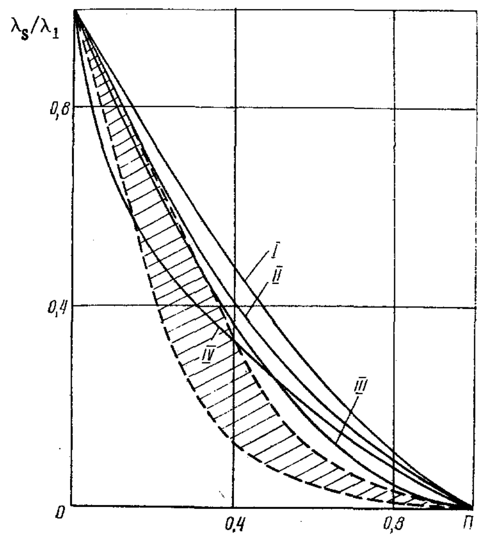

Fig. 1. Comparison of experimentally obtained skeletal thermal conductivity of fiber-metal wicks (hatched region) with calculations from equations in [4], [6], and [7].

Ferrell et al. [3], who investigated evaporation of the working fluid from materials based on copper, nickel, and steel fibers, also gave data on their thermal conductivity, which differed from the results of [2] by an order.

In [4] the thermal conductivity of liquid-saturated fiber-metal wicks are investigated. To determine the skeletal thermal conductivity in a direction parallel to the felting plane (i.e., along the fibers) Singh et al. recommended the relationship

$$\lambda_s = \lambda_1 (1 - \Pi) \exp(-\Pi), \tag{1}$$

which is graphically represented by line II in Fig. 1.

Dul'nev et al. [5, 6] devised theoretical models of their systems with chaotic and ordered structure. To calculate the thermal conductivity of fibrous materials of ordered structure (heat transfer across the fibers) they proposed the equation

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

which is represented by line III in Fig. 1. Calculation of the thermal conductivity for a model of chaotic structure gives a slightly different dependence on porosity (line IV).

Skorokhod simulated a fibrous system by interpenetrating randomly oriented cylinders. In this case the thermal conductivity is calculated from an equation whose real roots are given in Table 1 (line I in Fig. 1).

An analysis of models of heat conduction in fibrous systems shows that they have a significant deficiency – effects due to contact of the fibers are ignored (the contacts are regarded as ideal).

The aim of the present work was to investigate the skeletal thermal conductivity of sintered wicks made of copper, nickel, stainless steel, and Nichrome fibers and to determine the dependence of the thermal conductivity on the fiber material, porosity, and fiber diameter.

We determined experimentally, by the steady-state comparison method, the skeletal thermal conductivity (in a direction perpendicular to the felting plane) of specimens whose characteristics are given in Table 2. The temperature range in the experiments was 18-35°C. The temperature was measured with copper–Constantan thermocouples of diameter 0.16 mm connected to a semiautomatic R-348 potentiometer of accuracy class 0.002. The heat flux of 0.5-5 W was measured with a D-57 standard wattmeter of class 0.1. The heat flux and the temperature distribution in the specimens, measured when the operation of the apparatus was steady (after 1-2 h), was used to calculate the skeletal thermal conductivity by two methods – the absolute method,

TABLE 2. Skeletal Thermal Conductivity of Fiber-Metal Wicks

Material	d_f, μ	Π, %	λ_1, W/m·deg	λ_s, W/m·deg	Error, %
Copper	20	21,1	395	240	±3
		35,2		139	±3
		50,0		66,5	±5
		66,4		20,9	±5
		79,8		7,31	±7
		89,5		3,16	±10
		96,1		1,9	±10
	40	19,9	395	201	±3
		35,6		98	±5
		49,7		40	±7
		64,9		13,4	±7
		79,9		4,54	±10
		88,9		2,57	±10
	70	19,8	395	174	±3
		36,0		72,1	±5
		49,8		27,6	±5
		65,1		9,72	±7
		78,3		4,15	±10
Steel 1Kh18N9T	30	35,1	13,7	5,36	±5
		66,0		0,78	±7
		80,5		0,30	±7
Nickel	50	34,4	66	26,46	±7
		65,5		3,35	±7
		80,6		1,26	±7
Nichrome Kh20N80	50	10,6	12,5	10,4	±3
		20,6		8,24	±5
		35,4		5,09	±5
		50,3		2,58	±5
		65,5		0,88	±7
		80,3		0,315	±7
Nickel [2]	16	66,4		0,848	±12
		84,2		0,398	±20
		89,8		0,312	±20
Copper [2]	43	68,8		17,5	±7
		81,8		8,5	±7
Steel [3]		58		4,2	
		80		1,18	
		89		0,743	
Nickel [3]		61		16,6	
		82		2,98	
Copper [3]		59		22,3	
Nichrome [13]	50	26		3,45	
		38		1,7	
		42		1,5	
		54		0,95	

$$\lambda_s = \frac{q\delta_1}{\Delta t_1}, \tag{3}$$

and the comparison method,

$$\lambda_s = \lambda_{st}\frac{\delta_1}{\delta_{st}}\cdot\frac{F_{st}}{F_1}\cdot\frac{\Delta t_{st}}{\Delta t_1}. \tag{4}$$

The specimens were cylinders 30 mm long, 27.6 mm in diameter, composed of fibers with l_f/d_f = 45, 60, 75, 100, and 150.

Reference cylinders of corresponding dimensions were made of pure lead (99.99%) and aluminum (99.8%) by casting in vacuum.

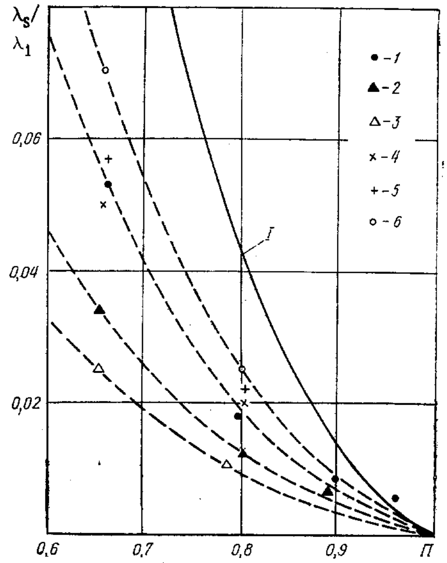

Fig. 2. Skeletal thermal conductivity of fiber-metal wicks as a function of porosity: 1) copper (d_f = 20 μ); 2) copper (d_f = 40 μ); 3) copper (d_f = 70 μ); 4) nickel (d_f = 50 μ); 5) stainless steel (d_f = 30 μ); 6) Nichrome (d_f = 50 μ). I – calculation from Eq. (2) in [5, 6].

Calibration experiments showed that the thermal conductivity of the two lead standards in the assembly was 34.65 W/m · deg for the first and 34.45 W/m · deg for the second. In all the experiments the thermal conductivity of lead was taken as 34.7 W/m · deg at 20°C according to [8, 9], since the temperature of the standards varied from 18 to 24°C and the temperature coefficient of the thermal conductivity of lead is low (0.015 W/m · deg^2). The thermal conductivity of pure aluminum in the aluminum –lead assembly was 231 W/m · deg, determined by the comparison method, and 233 W/m·deg, determined by the absolute method. The tabulated value of the thermal conductivity of aluminum is 228.5 W/m·deg at 25°, according to [8, 10].

The difference between the values of the thermal conductivity of the investigated specimens, determined by the two methods, did not exceed 5%, except for specimens of maximum porosity, where it was about 10%. The skeletal thermal conductivity of fiber-metal wicks, determined by the comparison method in several series of experiments, and also the errors of the experimental results are given in Table 2. The thermal conductivity of the wicks varied greatly with change in porosity and fiber diameter. The suggestion that the fiber diameter affects the thermal conductivity was expressed as far back as in [2], but was not confirmed by experiment. The disagreement between the experimental results and the data of [2, 3] is obviously due not so much to differences in the diameter, length, and thermal conductivity of the fiber material, as to the different conditions of felting, pressing, and sintering of the fibers, and to differences in experimental procedure.

A comparison of the experimental results with theoretical calculations [5-7] showed that in the region of low porosity the skeletal thermal conductivity data were in good agreement with the results of theoretical relationships based on the assumption of ideal contact between the fibers. At porosities above 30-40% the disagreement was very large (Fig. 1). The difference between theory and experiment was particularly pronounced for copper fibers of large diameter (Fig. 2). This disagreement is accounted for by the results of investigation of sintering of materials of fiber-metals. Kostornov et al. [11, 12] demonstrated by measurement of the electrical conductivity and by metallographic analysis that owing to the difference in number and quality of contacts in the initial pressings the quality of the sintered materials deteriorated with increase in porosity. Only structures with porosity up to 40% had perfect contacts. They also found that an increase in fiber diameter led to a rapid deterioration in sintering quality due to reduction of the ratio of the transverse dimension of the formed contacts to the fiber diameter.

NOTATION

П	is the porosity;
λ_s	is the skeletal thermal conductivity;

λ_1	is the thermal conductivity of fiber material;
$\nu = \lambda_2/\lambda_1$	is the ratio of thermal conductivity of gas (air) to thermal conductivity of fiber material;
q	is the density of conducted heat flux;
δ_1, δ_{st}	are the distances between temperature measurement points in specimen and standard;
Δt_1, Δt_{st}	are the temperature drops in specimen and standard;
F_1, F_{st}	are the cross-sectional areas of specimen and standard;
l_f/d_f	is the ratio of fiber length to fiber diameter.

LITERATURE CITED

1. H. R. Kunz, L. S. Langston, B. H. Hilton, S. S. Wyde, and G. H. Nasnick, "Vapor-chamber fin studies," NASA, CR-812 (1967).
2. M. M. Soliman, D. W. Graumann, and P. J. Berenson, "Effevtive thermal conductivity of dry and liquid-saturated sintered fiber-metal wicks," ASME Paper, 70-HT/SpT-40 (1970).
3. J. K. Ferrell, E. G. Alexander, and W. T. Piver, "Vaporization heat transfer in heat pipe wick materials," AIAA Paper, No. 256 (1972).
4. B. S. Singh, A. Dybbs, and F. A. Lyman, "Experimental study of the effective thermal conductivity of liquid saturated sintered fiber-metal wicks," Intern. J. Heat Mass Transfer, 16, No. 1 (1973).
5. G. N. Dul'nev, Yu. P. Zarichnyak, and B. L. Muratova, in: Heat and Mass Transfer [in Russian], No. 7, Nauka i Tekhnika, Minsk (1968), p. 82.
6. G. N. Dul'nev and Yu. P. Zarichnyak, Thermal Conductivity of Mixtures and Composite Materials [in Russian], Énergiya, Leningrad (1974).
7. V. V. Skorokhod, Poroshk. Metallurg., No. 6 (1967).
8. N. B. Vargaftik (editor), Thermophysical Properties of Substances [in Russian], Gosénergoizdat, Moscow–Leningrad (1956).
9. G. W. Kaye and T. H. Laby, Tables of Physical and Chemical Constants and Some Mathematical Functions, 13th ed., Wiley (1966).
10. V. S. Chirkin, Thermophysical Properties of Nuclear-Engineering Materials [in Russian], Atomizdat, Moscow (1968).
11. A. G. Kostornov, V. V. Skorokhod, and M. S. Shevchuk, Poroshk. Metallurg., No. 1 (1972).
12. A. G. Kostornov, V. V. Skorokhod, and M. S. Shevchuk, Poroshk. Metallurg., No. 2 (1972).
13. I. N. Frantsevich (editor), Composite Materials of Fibrous Structure [in Russian], Naukova Dumka, Kiev (1970).