σ is the surface tension, N/m;
P is the heater power, W.

Subscripts

c is the condenser;
e is the evaporator;
l is the liquid;
a is adiabatic;
av is the average;
in is internal.

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STRUCTURE PARAMETERS OF METAL-FIBER HEAT PIPE WICKS

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The results of an experimental investigation of local and average values of permeability and effective pore diameter for metal-fiber wicks, using a laser-Doppler velocity measurement, are presented and discussed.

Capillary-porous structures made of metallic individual fibers or powder are used successfully as the wicks of heat pipes [1]. Existing methods of preparing powdered and fibrous materials do not yield completely uniform structures for these materials. The properties differ with direction and cross-sectional area.

One of the most important characteristics governing the choice of structure for a specific application is the permeability. The methods of measurement in [2] usually give the average value the specimen permeability, from which one cannot assess local nonuniformities. The authors of [3-5] tried to solve this problem by measuring the rate of filtration with thermisistors of miniature tubes displaced along the specimen surface. The defects of these methods are that they give indirect information, require calibration, have inertia, and cannot measure a rate of filtration that varies with time. In addition, the range of the measured quantity is quite narrow. A new method was suggested in [6]. However, here also one cannot avoid errors introduced by the source of thermal pulses.

The present paper studies the basic properties of permeable capillary-porous bodies using a laser-Doppler velocity measurement (LDVM). With this method one can obtain local permeability coefficients K_i, the distribution of pore diameters with size, the dimension of the maximum and minimum pores, and their number. With this information one can estimate the quality of the material, compare its characteristics with other types of structures, and reach a conclusion as to the suitability of a specific manufacturing technique for specific items. It is also possible to carry out tests to reject items with a large scatter in their properties.

The measurements were carried out on an equipment whose main element is a type LG-75 gas laser. The working section is a hollow cylinder with an inlet for gas carrying scattering particles and a pressure pickoff. The specimen is attached in the upper part in such a way that the gas flow passes through the entire section of the porous insert. Sealing is done at the end section on the mount surface (Fig. 1).

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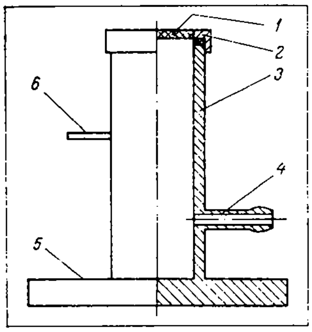

Fig. 1

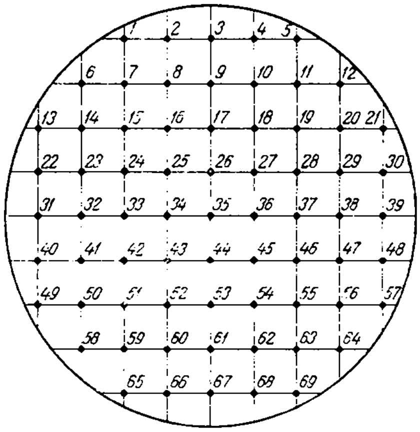

Fig. 2

Fig. 1. Schematic of the working section of the experimental equipment: 1) capillary-porous specimen; 2) sealing ring; 3) casing of the air chamber; 4) air supply fitting; 5) base of air chamber; 6) fitting for pressure pickoff.

Fig. 2. Location of the measurement points on the surface of the test specimens.

TABLE 1. Characteristics of the Test Specimens

Specimen No.	Spec. thickness δ, mm	Diam. initial fibers d_f, μm	Porosity П; %
1	1,7		61,8
2	1,5		66,1
3	1,7	40	73,2
4	1,2		77,2
5	1,5		78,1
6	1,0		80,9
7	2,0		62,8
8	1,9		74,1
9	1,7	20	79,3
10	0,6		80,5
11	1,1		82,3

With this arrangement one can carry out the measurement with a noncontact method. In addition, calibration is not required. The experimental error results only from errors in the instrments used, and is 3%. This error can be reduced with minor changes in the optical system.

Investigations were carried out with specimens made of discrete copper fibers of length 3 mm. The specimen diameter and thickness was 28 mm and 1.5-2 mm. The specimens were soldered to a mandrel, their surface was arbitrarily divided into 69 sections (Fig. 2), and the rate of gas filtration was measured at the center of each section. The light rays intersected at a distance of 1.5 mm from the surface. The specimens were manufactured with varying average porosity (Table 1).

Air with scattering particles of diameter 1-3 μm passed through the specimen and arrived at the region of intersection of the rays at the measurement point. The dimensions of the scattering particles and their concentration in the air (1:30,000) could not cause clogging of the specimen pores. Moreover, the test time for one specimen was 30-45 min, which also reduced the danger of varying the passage diameter of the pores.

For all the specimens the distribution of local filtration velocities over the surface was obtained. Since the dependence of filtration rate on pressure gradient is linear [7] in the range of pressure drop tested (up to 400 N/m^2) the local permeability coefficients required for the calculation were obtained from the Darcy law in the form

$$V_i = \frac{K_i}{\mu} \cdot \frac{dp}{dx}\,. \tag{1}$$

TABLE 2. Basic Parameters for Specimen No. 6 along Two Mutually Perpendicular Diameters

V_i, cm/sec	$K_i \cdot 10^{11}$, m^2	D_i, μm	V_i, cm/sec	$K_i \cdot 10^{11}$, m^2	D_i, μm
20,6	18,9	86,6	21,1	19,4	87,7
24,3	22,3	94,0	23,1	21,2	91,7
21,1	19,4	87,7	25,8	23,7	96,8
23,8	21,9	93,0	27,7	25,5	100,5
28,4	26,1	101,6	21,1	19,4	87,7
21,1	19,4	87,7	19,8	18,2	84,9
25,1	23,1	95,6	23,8	21,9	93,0
21,8	20,0	89,0	17,2	15,8	79,0
22,4	20,6	90,4			

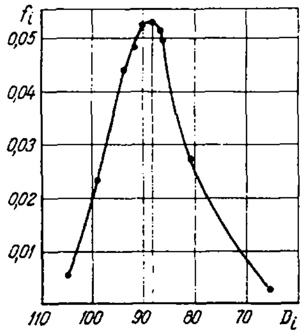

Fig. 3. Differential pore-size distribution for specimen No. 6 (D_i is the pore size, μm; f_i is the probability density distribution, 1/μm).

Equation (1) can be integrated to obtain an expression for K_i.

The pore dimensions were obtained using a method based on simultaneous solution of the Darcy and Poiseuille–Hagan equations [8]. Here one finds the pore diameter of an ideal porous medium with hydraulic resistance equal to that of the actual porous body under the condition that the pressure loss in the real and the ideal porous body are equal for the same velocity of motion of the filtered substance. Table 2 shows local filtration velocities, permeability coefficients, and pore diameters for specimen No. 6 at points lying on two mutually perpendicular diameters. It can be seen that for a specimen with average porosity Π = 80.9% the average pore diameter is $\bar{D}$ = 89.4 μm. The main deviation is 7.4 μm, and the range, i.e., the difference between the largest and smallest local values of diameter, is 41.6 μm. The probable error, the absolute error, and the modulus of precision are 4.9 μm, 5.9 μm, and 0.1 1/μm, respectively. With a confidence limit of 0.9, the average pore diameter is in the range 77.3-101.5 μm.

For all values D_i we determined the probability density of the distribution

$$f_i = \frac{1}{\sqrt{2\pi}\,\sigma} \exp\left[-\frac{(D_i - \bar{D})^2}{2\sigma^2}\right] \quad (2)$$

and constructed differential pore-size distributions. For specimen No. 6 the differential distribution has the form shown in Fig. 3. The asymmetry, and the excess, describing the deviation of the distribution obtained from a normal one, are 0.34 and 0.92, respectively.

Analysis of the data obtained for all the test specimens showed that the average pore diameter increases with increase of porosity (e.g., for Specimens Nos. 1-6 $\bar{D}$ varies from 38.8 to 89.4 μm, and for Specimen Nos. 7-11 the increase in $\bar{D}$ observed is from 26.7 to 57.5 μm). The main deviation σ here tends to increase from 2.85 to 7.4 for Nos. 1-6, and from 2.1 to 5.2 for Nos. 7-11.

TABLE 3. Comparison of the Characteristics of Porous Specimens Made of Bronze and Stainless Steel Powders, and Dispersed Copper Fibers

Literature source	Orig. material	Av. pore diameter $\bar{D}$, μm	Deviation σ, μm	Excess E	Asymmetry, A
Reference [8]	Stainless steel powder	31,2	7,1	—0,05	1,38
		42,9	14,9	—1,95	1,05
		58,3	26,0	1,34	1,14
		66,5	24,1	0,60	1,02
		76,6	28,1	—0,90	0,24
		77,6	31,0	0,90	0,86
	Bronze powder	58,4	12,21	0,24	—0,80
		60,6	12,49	—0,8	—0,18
Present investigation	Copper fibers d_f = 20 μm	26,7	2,14	—1,09	0,14
		39,9	2,96	0,93	—0,77
		57,5	5,23	—1,15	—0,02
		59,2	5,59	—0,53	—0,57
		61,5	4,45	—0,93	0,03
	Copper fibrers, d_f = 40 μm	38,8	2,85	—0,58	0,75
		44,9	5,24	—0,13	0,67
		52,8	4,36	—0,97	0,16
		71,3	4,37	—0,22	—0,15
		89,4	7,36	0,92	—0,34
		97,4	8,67	0,23	0,45

There is a corresponding increase also in the range. For example, for Specimens Nos. 1-6 the range varies from 10.6 to 41.6, and for Specimens Nos. 7-11 it varies from 7.5 to 19.1. The probable and the absolute errors also increased: 1.9-4.9 μm for Nos. 1-6 and 1.4-3.5 μm for Nos. 7-11.

From the above it can be seen that the uniformity of structure deteriorates with increase in the porosity. For a given porosity there is an improvement in uniformity of structure by reducing the diameter of the original fibers. For example, the deviation σ describing the degree of uniformity of porous materials (the smaller is σ, the more uniform is the structure) for Specimen No. 6 (Π = 80.9%, d_f = 40 μm) is 8.67, and for Specimen No. 11 (Π = 82.3%, d_f = 20 μm) σ = 4.45. A decrease in the fiber diameter also improves the other characteristics governing the uniformity of structure, i.e., it reduces the difference between the extreme diameters of the pores, the range, and the absolute and probable errors.

The asymmetry in the distribution of A for all the specimens investigated varied from −0.77 to +0.75 (the smallest value is −0.02), and the excess E from − 1.15 to 0.93 (the smallest value is − 0.13). The modulus of variability, describing the scatter of local pore diameters about the average value, varied from 6.1 to 11.7%.

When comparing the uniformity of capillary-porous materials of different structure one must choose a structure with close pore dimensions, since the absolute value of σ depends also on the absolute value of the average pore size.

Table 3 shows values of σ, E and A for porous specimens made of stainless steel and bronze powder with diameter of spherical particles of 125-160 μm [8], and also data obtained in the present investigation. From Table 3 it can be seen that, in terms of the all characteristics of the structures of metal-porous construction, the most uniform capillary-porous materials are those sintered from powders.

NOTATION

K	is the permeability coefficient, m^2;
V	is the filtration rate, m/sec;
μ	is the viscosity, $N \cdot sec/m^2$;
dp/dx	is the pressure gradient;
σ	is the rms deviation;
f_i	is the probability density distribution, μm^{-1};
D	is the pore diameter, μm;
E	is the excess;
A	is the asymmetry.

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MAXIMUM HEAT FLUX IN PLANAR METAL-FIBER WICKS UNDER CONDITIONS TYPICAL OF HEAT PIPES

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Experimental results of an investigation of the limiting heat flux for surfaces covered with a metal-fiber wick for different angles of inclination and variable length of the transport section are presented and discussed.

The investigation of evaporation and boiling of liquids on a plane surface covered with a metal-fiber wick gives a data base for elucidating the physical conditions for the heat-transfer process in the heat supply zone, and for choosing the optimal geometric and structural parameters of the wick. The capillary-transport properties of metal-fiber wicks were studied in [1-3], and the authors were able, to a first approximation, to optimize the structural parameters of materials made of baked discrete monodispersed fibers. However, to improve the method of designing heat pipes and heat-transfer agent distributions in film evaporators, additional investigations are required of the transport capabilities of metal-fiber wicks under heat-transfer conditions.

One of the most important characteristics of heat-transfer devices, including heat pipes, is the maximum heat flux transmitted under normal operating conditions.

The maximum heat flux Q_{max} in the heat zone of low-temperature heat pipes is very often a limit on the capillary transport of the heat-transfer agent [4-6], and depends on the structural and constructional characteristics of the porous material, the thermophysical properties of the working liquid, and also the heat pipe operating conditions.

The simultaneous solution of the equations of conservation of mass, energy, and momentum for an element of a metal-fiber wick [7] can be written in the form

$$Q_{max} = 4N \frac{k_w}{D_{ef}} \cdot \frac{F_w}{0.5\,(L_e + L_c) + L_a} \left(1 - \frac{\Delta P_g}{\Delta P_c}\right). \tag{1}$$

It can be seen from Eq. (1) that, for correct choice of the working liquid, to ensure a maximum value of the parameter $N = \sigma\rho_l r/\mu_l$, wicks characterized by good capillary-transport capabilities (a maximum of the parameter k_w/D_{ef} and of the capillary head ΔP_c) are more efficient. It is clear also that Q_{max} is affected by the cross-sectional area F_w of the wick, and the reduced filtration length $0.5\,(L_e + L_c) + L_a$.

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