PROMISING APPLICATIONS OF HIGH-POROSITY CELLULAR MATERIALS IN HEAT PIPES

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The authors present results of an experimental investigation of the structural, stress, trasnport and thermophysical properties of high-porosity cellular materials as applied to the capillary structures of heat pipes.

The most promising method of artificial cooling of electrical equipment is to use heat pipes designed to intensify heat transfer and achieve minimal thermal resistance in the heat output circuit within the range of the electrical equipment. At present there is no universal heat pipe for these purposes. This stems from the diversity of the components, the differing operating conditions of equipment, and the imperfect technology of manufacture of heat pipes and their capillary structures [1].

The capillary structures of heat pipes play a major role in such physically important processes as phase transitions and heat and mass transfer; in the final analysis they determine the heat transfer capability of the heat pipe. Although the number of published papers, both in the USSR and abroad, is quite large, the investigation of the properties of capillary structures aimed at perfecting heat transfer in heat pipes is far from complete. One can note that for the simmplest models of capillary systems the description of the processes of heat and mass transfer can be reduced to describing the process in an individual cylindrical capillary, followed by averaging over the distribution function of pores by size. However, this approach gives an incorrect result in describing the corresponding mechanisms of transfer in capillary systems, where the interaction of pores of different sizes plays a dominant role.

The need to expand the circle of capillary structures investigated and to accumulate experimental data is dictated not only by the absence of reliable theoretical prediction of the processes of heat and mass transfer in such systems, but also by practical requirements relevant to the different spheres of application of heat pipes.

A great part of the investigations of the capillary structures of heat pipes is aimed at the study of structural, capillary-transport and thermophysical characteristics. The strength properties of capillary structures, as a rule, do not play a noticeable role, since the body in most cases the cylindrical heat pipe geometry makes the heat pipe rigid. However, a planar heat pipe geometry is the most appropriate, since the heat liberating element in electrical equipment is either itself planar, or is designed to attach to plant surfaces. The strength properties of capillary structures become noticeable when one builds planar heat pipes of great size in the plane, and thin heat pipes with external dimensions typical of electrical plates and other planar electric applicances (100 × 200 × 3 mm).

The present paper proposes the use, based on results of various investigations, of new capillary structures for heat pipes, i.e., high-porosity cellular materials.

The method of obtaining these materials is bsed on reproducing the matrix, the high-porosity structure of a latticed-cell polymer (LCP), e.g., polyurethane foam. The scheme of this process has been presented in a handbook [2].

The spatial structure, size and shape of pores of these high-porosity materials are given by the actual structure of the latticed-cell polymer used as a matrix, very often polyurethane foam. The advantage of this foam is that the volume of material in it (polyurethane) is 2.5

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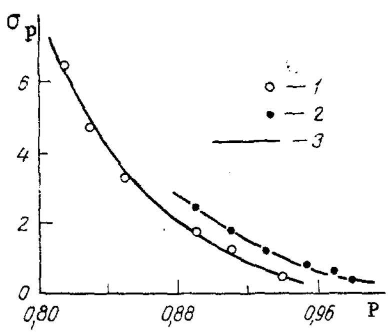

Fig. 1

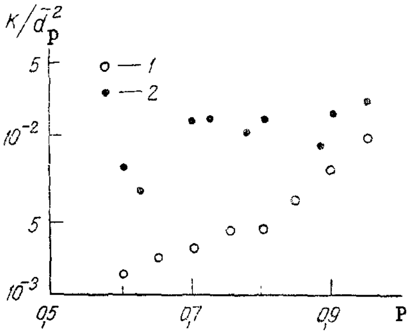

Fig. 2

Fig. 1. Temporal resistance σ_p, in MPa, of high-porosity cellular materials as a function of the porosity P: 1) material made of copper; 2) material made of nickel; 3) as computed by Eq. (1).

Fig. 2. Ratio $K/\bar{d}_p^2$ as a function of the porosity P: 1) material made of copper; 2) material made of nickel [2, 3].

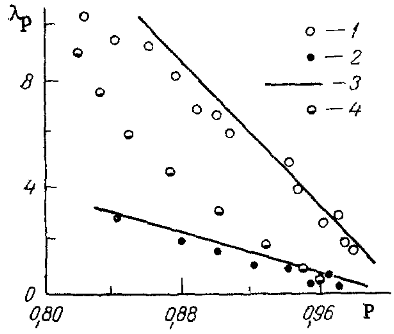

Fig. 3

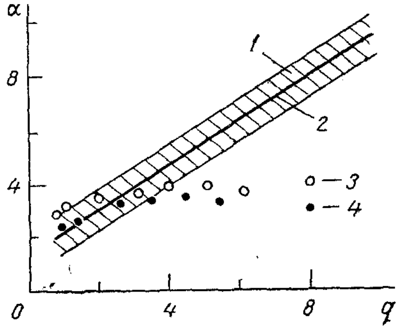

Fig. 4

Fig. 3. Body thermal conductivity λ_k, W/(m·K) as a function of the porosity P: 1) foam material made of copper; 2) foam material made of nickel; 3) as computed from Eq. (2); 4) fiber material made of copper [3].

Fig. 4. Heat transfer coefficient $\alpha\cdot10^{-4}$, $W/(m^2\cdot K)$, as a function of the heat flux density $q\cdot10^{-5}$, W/m^2, in boiling of water in capillary structures: 1) region corresponding to the experimental data of [4]; 2) the dependence $\alpha = 5.68\cdot q^{0.7}$ [4]; 3) cellular material made of copper (P = 0.92, cell diameter d_c = 0.06 mm); 4) cellular material made of nickel (P = 0.95, cell diameter d_c = 0.7 mm).

TABLE 1. Parameters of Heat Pipes with Capillary Structures Made of Cellular Material

Heat pipe No.	Number of items	Dimensions of heat pipe					Characteristics of capillary structure		Heat transfer agent
		d, mm	a, mm	L, mm	δ, mm	δ_K, mm	$\delta_{K.c}$, mm	P, %	
1	1	28	—	300	—	1	2,5	92	Water
2	1	16	—	350	—	1	1,5	90	»
3	3	10	—	325	—	1	1,0	88	Water, acetone
4	3	6	—	300	—	1	1,0	88	»
5	1	—	100	200	5	1	3,0	85	Water
6	1	—	100	200	4	0,5	3,0	83	»
7	1	—	100	200	3	0,4	2,2	83	»

<u>Note</u>. The material of the heat pipe body and the capillary structure is copper.

TABLE 2. Basic Characteristics of Heat Pipes with Cellular Materials

Heat pipe No.	External dimensions of the heat pipe body, mm	Length of zones, mm		Cooling conditions of the condensation zone (longitudinal washing with water flow)	Q_{max}, W		$t^{evap}_{wall\,max}$, °C (at Q_{max})		$R_{heat\ pipe}$, K/W (at Q_{max})	
		L_{evap}	L_{cond}		$\varphi=0$	$\varphi=90°$	$\varphi=0$	$\varphi=90°$	$\varphi=0$	$\varphi=90°$
1	⌀28×300	65	110	$G=20$ g/sec, $t=30$ °C	>1600	—	130	—	0,05	—
2	⌀16×350	100	100	$G=20$ g/sec, $t=30$ °C	500	—	150	—	0,10	—
3	⌀10×325	65	110	$G=2$ g/sec, $t=25$ °C	200	50	150	125	0,5	2
4	⌀6×300	65	110	$G=2$ g/sec, $t=25$ °C	75	20	70	125	0,7	3
5	200×100×5	65	65	$G=10$ g/sec, $t=25$ °C	500	130	115	115	0,15	0,5
6	200×100×4	65	65	$G=10$ g/sec, $t=25$ °C	400	150	100	120	0,12	0,5
7	200×100×3	65	65	$G=10$ g/sec, $t=25$ °C	400	130	110	110	0,15	0,6

to 1.6%, with the remaining space occupied by voids (cells) which have a shape close to an ellipsoid of revolution with a mean diameter of 300-2000 μm (depending on the type of foam).

In the structure of a high-porosity cellular material, in addition to the basic celular porosity, there is channel porosity, formed by removal of the foam body in the thermal disintegration. The channel porosity forms a three-dimensional connected mesh and permeates through the entire foam structure.

Besides the cellular voids in the channel pores, the foam structure has micropores, due to dispersion of the original powder, to density of stacks of powder in the dried suspension, to the sintering conditions, etc.

Thus, of the total foam porosity (P = 0.8-0.98), the fraction of pores formed by channel porosity and microporosity and having the dimensions (10-50) μm, is up to 10%. The presence of channel pores and micropores and their interaction with cellular pores appreciably influences many properties of the high-porosity cellular materials and promotes the flow of capillary processes.

For practical purposes there is interest in a comparative generalization of the properties of porous permeable materials with respect to the property of interest, the porosity. For materials a typical range of porosity in the region of high values of this parameter is (P = 0.8-0.98), and therefore from the general literature of porous permeable materials in this range of porosity one can single out porous fiber materials, and compare the properties of foam and fiber.

The strength properties of foam materials, important for planar heat pipes, are due primarily to the three-dimensional nature of the foam structure, and the magnitude and quality of the interparticle contact of the structural elements. To evaluate the strength properties of porous materials we use the conventional characteristics: time resistance, strength limits in compression and shear, relative elongation, etc.

The values of time resistance typical of foam materials with P > 0.8 are shown in Fig. 1. These data are approximated well by the formula of M. Yu. Bal'shin, relating the relative time resistance and the porosity:

$$\sigma_p/\sigma_{cm} = (1-\Pi)^m. \tag{1}$$

The power index m = 1.9-2.1 depends on the cells and the material.

The known data on strength properties of fiber materials refer to a porosity of P < 0.8, and therefore a straight comparison of the strength properties of fiber and foam materials is difficult.

An important property of the capillary structure of heat pipes is their permeability. The maximum permeability of a structure of porous material is required in practically all cases to achieve a minimum pressure loss of the filtered medium (the heat pipe heat transfer agent). It is known that, other things being equal, porous materials made of smooth fibers and spherical particles have the largest permeability. It is appropriate to compare the permeability of capillary structures in the coordinates $K/\bar{d}_h^2 - P$ (Fig. 2). From the data presented it can be seen that for the usual mean pore sizes the permeability of fiber material is higher than for cellular materials, and that as the porosity increases the values of $K/\bar{d}_h^2$ for cellular and fiber materials tend to come together.

The thermal conductivity of the cellular material body was investigated by measuring the thermal conductivity of ITÉM-1, based on a quasi-steady comparative method. The experimental data, shown in Fig. 3, can be approximated comparatively well by the formula

$$\lambda_p = K_s \lambda_M (1 - \Pi). \tag{2}$$

The structural coefficient (K_s) for the cellular material with cells in the form of pentagons is $K_s = 0.2$.

From the data shown it can be seen that with high porosity the body thermal conductivity of cellular material is higher than for fiber material [3]. The reason is the more complete interparticle contacts of structural elements of the cellular material.

The study of heat transfer with water boiling in filled and unfilled copper and nickel capillary structures and capillary materials was performed on an equipment analogous to that of [4]. Figure 4 shows the results of an experimental investigation of heat transfer with boiling in test specimens of cellular material of cell size 0.6-0.7 mm and porosity $P > 0.9$, and compares them with available literature data.

It should be noted that the results obtained agree well with the data of [4] in the region of heat flux $q = (10\text{-}40)\cdot 10^4$ W/m^2. At larger heat flux the heat transfer coefficient with boiling of water in the test specimens is lower than in the specimens investigated in [4]. This noticeable deviation of the heat transfer coefficient in cellular materials at heat flux densities higher than $q = 40 \cdot 10^4$ W/m^2 from the known data on heat transfer in capillary structures is linked to the specific structure of the cellular materials, and the interaction of pores of substantially different sizes has a dominant influence on the heat transfer.

From the investigtions of structural, strength, transfer and thermophysical properties of cellular materials and the comparative analysis of other capillary structures one can propose them as promising heat pipe capillary structures, close in their properties to the better capillary structues used in the classical heat pipe structures. The technology of manufacturing heat pipes with capillary structures of cellular material, the possibility of creating good contact between the heat pipe body and the cellular material by dross-type sintering, and the formation of a thin layer of finely porous substrate between the heat pipe body and the cellular material, are all prerequisites for the wide use of heat pipes with capillary structure made of cellular material.

In this work we have investigated experimentally the heat transfer characteristics of the cylindrical and planar classical heat pipe structures. The structural parameters of the main heat pipe test specimens and the characteristics of their capillary structures and heat transfer agents are shown in Table 1.

The experiments were conducted on a facility with a known layout [3], of which the basic element was a heat pipe set up for the tests by having thermocouples welded to the pipe body. The heat supply to the heat pipe was by ohmic heating, and heat was removed by forced flow of a temperature-controlled liquid. The maximum heat flux was determined from the sharp variation in the shape of the functional dependence of the heat pipe body wall temperature at the extreme section of the heat supply zone on the heat flux transferred. The thermal resistance of the heat pipe was determined from the maximum temperature difference of the walls of the heat pipe body at the extreme secitons of the heat supply and removal zones, referenced to the heat flux transferred.

Analysis of the experimental data from investigation of the heat transfer parameters of heat pipes with cellular materials shows the good capability of the heat pipes tested with a favorable orientation ($\varphi=0$, $\varphi=-90°$) in the gravity field. For convenience of analysis the required data are shown in Table 2. With an unfavorable orientation ($\varphi=+90°$) the heat transfer parameters of the heat pipe with cellular material deteriorate appreciably (as is true of all classical heat pipes).

The advantages of a heat pipe with cellular material lie in the construction of plnar heat pipes, requirng rather a rigid capillary structure to achieve rigidity of the heat pipe structure. The evidence for this is the experimental data of heat pipes numbers 5, 6, and 7.

Thus, by using cellular materials as capillary structures, easily welded to the heat pipe body, and possessing enhanced strength properties with a porosity of more than 80%, one can build high-efficiency heat pipe structures which will fill the gap, to a certain extent, existing in practice in the manufacture and use of heat pipe panels.

NOTATION

P, porosity; $\bar{d}_h$, mean pore diameter; d, external diameter of the heat pipe body; a, width of the heat pipe; L, L_e, L_c, length of the heat pipe, and of the evaporation and condensation zones; δ, δ_b, δ_{cs}, thickness of the heat pipe, the body, and the capillary structure; K, permeability; σ_p, σ_{cm}, temporal resistance of the porous and compacted material; α, heat transfer coefficient; q, heat flux density; λ_p, λ_m, thermal conductivity of the porous and compacted material; φ, slope angle of the heat pipe to the horizontal; Q_{max}, maximum heat flux; $t_{\text{wall max}}^{\text{evap}}$, maximum wall temperature of the heat pipe body in the evaporation zone; R_{heat}, thermal resistance of the heat pipe; G, mass flow rate.

LITERATURE CITED

1. A. A. Popova, Instruments and Equipment of Electronic Apparatus, A Review, Moscow (1987).
2. S. V. Belov (ed.), Porous Permeable Materials: Handbook, Moscow (1987).
3. M. G. Semena, A. N. Gershuni, and V. K. Zaripov, Heat Pipes with Metal-Fiber Capillary Structures, Kiev (1984).
4. L. L. Vasil'ev, S. V. Konev, P. Shtul'ts, and L. Khorvat, Inzh. Fiz. Zh., Vol. 42, No. 6, 893-898 (1982).

FLOW OF PURE GASES IN POLYETHYLENE TEREPHTHALATE NUCLEAR ULTRAFILTRATION MEMBRANES

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Measurements have been made on the surface flow of hydrogen, nitrogen, krypton, and xenon in polyethylene terephthalate membranes having pore sizes less than 15 nm. The gas-selective behavior is considered and surface molecular migration coefficients are estimated.

Measurements have been made on the flow of pure gases in nuclear polyethylene terephthalate PETP membranes particularly because new types of membrane have recently been made that show high selectivity [1, 2]. Gas compnents can be separated because of differences in the diffusion and dissolution constants (Henry constants). The decisive features are the structure and the pore shape and size.

Pores are usually etched in polymer films to produce highly productive membranes. Porous semipermeable membranes [3] and nuclear ones [4, 5] are made in that way. A porous semipermeable membrane may be made by treating an amorphous-crystalline PETP film with crystallizing solvent solutions [6, 7] to raise the throughput by 2-3 orders of magnitude. However, when the pores become much larger than the gas molecules, the selectivity is largely lost, particularly if there is a large spread in pore sizes.

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