

NOTATION

U, specific permeability of gas; D, diffusion coefficient; $V_a = \sqrt{8RT/\pi M}$, mean thermal velocity of molecules; T, temperature; R, universal gas constant; M, molecular weight; L_D , mean path length of molecules up to collision with surfaces of SVHI; δ , distance between adjacent layers of SVHI; ℓ , thickness of a stack of SVHI; ρ_i , packing density of gaskets; P_S , porosity of a screen; d_f , mean diameter of fibers in a gasket; d_S , diameter of a hole in the screen; ρ , density of the material of the fibers; α_S , α_i , probability of passage of molecules through the screen and gasket, respectively; m, weight of 1-m² gasket; δ_i , thickness of the gasket; ρ_S , packing density of screens; α_0 , probability of passage of molecules through a single layer [10]; δ_S , thickness of a screen; N_p , stacking density of layers of gaskets and screens; t, distance between holes.

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INVESTIGATION OF THE STRUCTURAL AND HYDRAULIC PROPERTIES OF CAPILLARY POROUS MATERIALS FOR HEAT PIPES

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The article analyzes the principal requirements regarding the properties of capillary porous materials for wicks of antigravitation heat pipes. Their porosity, coefficients of permeability and sinuosity are determined.

In the analysis of processes of heat and mass transfer in heat pipes, information on the properties of the capillary porous materials (CPM) used in them is of importance. On the

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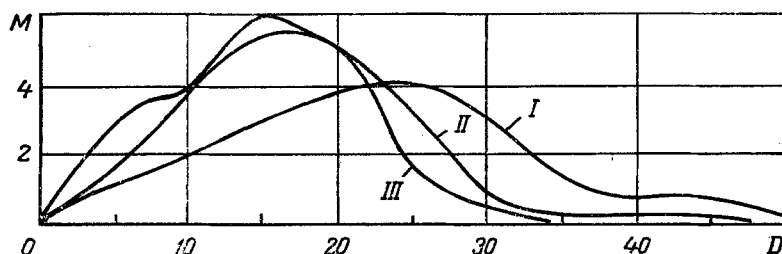


Fig. 1. Differential sedimentation curves of the particle weight distribution according to equivalent diameters of three types of titanium powder: I) $D = 26 \mu\text{m}$; II) $16 \mu\text{m}$; III) $14 \mu\text{m}$. M , %; D , μm .

other hand, the operating conditions, design features, and working characteristics of heat pipes determine the requirements that the properties of CPM have to meet. In particular, if effective heat transfer to a sufficient distance under arbitrary orientations in the gravitational field is to be ensured in antigravitation heat pipes (AGHP) [1, 2], finely porous capillary structures are indispensable. Such structures make it possible to attain high capillary potentials when liquids with low surface tension are used; among them are practically all low-temperature heat carriers. It is obvious that finely porous capillary structures with effective pore size of the order of $1\text{-}10 \mu\text{m}$ induce high hydraulic resistance which can be reduced chiefly by maximally increasing the porosity. Yet it is necessary to maintain the strength characteristics of the CPM so that it can be machined without the surface layer of pores being crushed and leveled.

From this point of view the most promising material is finely disperse metal powders from which capillary structures for AGHP with the required properties can be obtained by methods of powder metallurgy [3]. The present article submits the results of the investigation of the principal structural and hydraulic characteristics of CPM made from titanium powder with different particle size.

The initial powders obtained by the method of metallothermal reduction with calcium hydride have an irregular particle shape. Figure 1 shows the curves of particle size distribution of the investigated powders. For the purpose of systematization they were divided into four types according to particle size distribution:

Type of powder	Mean equivalent particle diameter, μm
1	26
2	18
3	16
4	14

Total porosity P was determined by comparison of the densities of porous and compact material, and open porosity P_0 was determined from the results of impregnation by the method of hydrostatic weighing. Figure 2 shows the dependence of P_0/P on P . It can be seen from the figure that in specimens with porosity greater than 25% all the pores are open. On this part of the graph the experimental points lie near the straight line $P_0/P = 1$ with an accuracy not poorer than 8%. When porosity drops to less than 25%, closed pores appear in the material, and their relative volume rapidly increases. When the porosity of the specimens amounts to 11-12% or less, it must be expected that all the pores become closed ones and that the specimen loses its permeability. In addition, the shape of the obtained dependence shows that as a result of machining pores in the material in the region of high porosities do not become closed because there is no noticeable decrease in the value of P_0/P in comparison with the expected one.

To determine the maximal effective pore radius r_M we used the method of expelling the liquid from the impregnated specimen (the Barus-Bechhold method). It must be noted that the value of r_M in heat pipes belonging to the type under consideration is the most important feature because it determines the capillary potential of the wick and the possibility of using the wick as a "hydraulic shutter" preventing overflow of vapor from the evaporating surface to the absorbing one. Evaluation of r_M is therefore mandatory for determining the heat transmitting ability of AGHP.

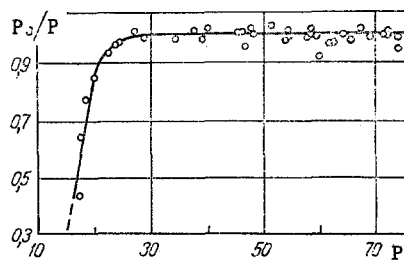


Fig. 2. Dependence of the ratio of open porosity to total porosity P_0/P on the total porosity P of capillary porous materials made of titanium powders. P , %.

To obtain reliable data by this method, the investigated specimens have to be thoroughly cleaned and impregnated with liquid. In addition, the contact wetting angle of the porous structure by the chosen liquid has to be known; it is not always known, and it differs from the angle for a smooth poreless surface.

We used the values of the cosine of the contact wetting angle determined in [4]. The results of measurements of r_M are shown in Fig. 3a. In the range of porosities from 54 to 74% the maximal pore radius changes from 3.5 to 11.0 μm , i.e., it increases more than three times. For porous materials belonging to all the four types of grain size distribution, the results for r_M coincide, and they can be described by a single curve. In calculating the parameters of the empirical dependences, both for r_M and for K and r_T , we used the least squares method. The dependence of r_M on total porosity is fairly well approximated by the following functions:

$$r_M = 27,6P^{3,5} \quad (1)$$

and

$$r_M = \frac{1}{0,83 - P} \quad (2)$$

Here and below, P is expressed in fractions of unity.

Formula (2) describes the experimental points more accurately than formula (1); the latter, however, is the most general approximation of data on pore size for a broad class of porous metals [5]. A dependence of the form of (1) describes well the results for porous materials obtained by pressing and rolling when their value of P does not exceed 40-50%. It was noted in [5] that in more highly porous specimens the pore size increases more rapidly than according to formula (1); this applies to a certain extent also to the results presented in Fig. 3a.

The coefficient of permeability of the CPM was calculated on the basis of Darcy's law for the laminar flow of a viscous incompressible liquid according to the results of measurement of the flow rate of water through a specimen under the effect of hydrostatic pressure of a column of liquid. To measure K is indispensable because it determines the mass flow rate of a liquid heat carrier through the shutting-off wall of the wick of the AGHP, and consequently it also determines the magnitude of heat transfer.

The experimental data on permeability are presented in Fig. 3b. For the four types of powder the obtained values agree well with each other, and they can be described by a power function of the form

$$K = 40P^{8,0} \quad (3)$$

Some scatter of the results is apparently due to the instability of filtration that was observed in the experiments. It is known [5, 6] that the coefficient of permeability is affected by factors such as the particle size distribution of the powder, the shape of the particles, the state of the surface of the pores, and some others. Nevertheless, the experimental points are grouped fairly closely about the curve calculated by (3), whose shape coincides with the known dependence [5]:

$$K = cP^n,$$

where c and n are some constants.

The principal characteristic of CPM determining the coefficient of permeability is porosity, i.e., K depends solely on the structure of the material and not on the surface phenomena on the interface. When porosity changes by a factor of 1.4, the coefficient of permeability changes from $0.25 \cdot 10^{-12}$ to $4.00 \cdot 10^{-12} \text{ m}^2$, i.e., 16 times.

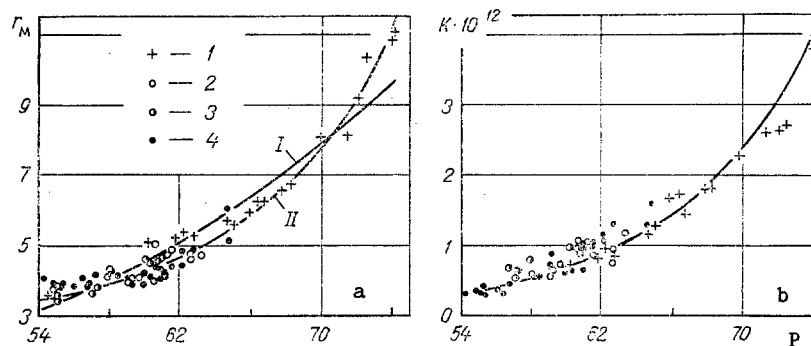


Fig. 3. Dependence of the maximal pore radius (a) and of the coefficient of permeability (b) on the total porosity of CPM from titanium powders with different particle size distribution. Curves I and II were calculated by formulas (1) and (2), respectively. Here and in Fig. 4 the numbering of the dots corresponds to the classification of the powders according to types. r_M , μm ; K , m^2 .

From the results of measurements of P and K we calculated the mean hydraulic pore radii by the formula known from [7]

$$\bar{r}_T = \sqrt{\frac{8K}{P}}. \quad (4)$$

Formula (4) was obtained from the joint solution of the Darcy and the Hagen-Poiseuille equations, and it determines some mean radius of the straight cylindrical pores of material that is identical with real material in thickness and hydraulic resistance. Therefore \bar{r}_T is always smaller than the actual mean pore radius. To bring the calculated and the true value of the radii closer together, we introduced the correction factor a , the so-called coefficient of sinuosity, and with it taken into account

$$\bar{r}_T = a \sqrt{\frac{8K}{P}}. \quad (5)$$

To determine it, Berkman and Mel'nikova [7] suggested using the formula

$$a = \frac{r_M}{\bar{r}_T}, \quad (6)$$

where \bar{r}_T is the mean pore radius calculated by formula (4).

The results of calculating \bar{r}_T by formula (4) and a by formula (6) are presented in Fig. 4a and b, respectively.

A comparison of the experimental results shows that, regardless of some scatter, the values of \bar{r}_T in the range of porosities from 54 to 74% are grouped around the straight line calculated by the formula

$$\bar{r}_T = 20,5P - 9,0. \quad (7)$$

The coincidence of the values of the mean pore size determined for porous materials from powders with different particle size distribution shows that \bar{r}_T is affected chiefly by porosity, and less by other factors. However, it must also be borne in mind that specimens produced by the same technology are obtained from powders that are equal in shape and similar in grains size distribution, and apparently therefore also have similar values of \bar{r}_T since they are equal in porosity.

In the entire range of change of porosity, the mean hydraulic pore radius changes from 2.0 to 6.5 μm , and a comparison with Fig. 3a shows that \bar{r}_T is fairly close to the maximum radius r_M . A similar closeness of r_M and \bar{r}_T for highly porous specimens was noted earlier on, in [5, 8]. For materials with high porosity the difference between r_M and \bar{r}_T practically vanishes, and $r_M/\bar{r}_T \rightarrow 1$.

With equal porosity, the highest values of the coefficient of sinuosity (see Fig. 4b) are found in materials made from the coarsest powder, i.e., type 1, and the lowest at values in powders of the 4th type. When porosity changes from 54 to 74%, the values of the co-

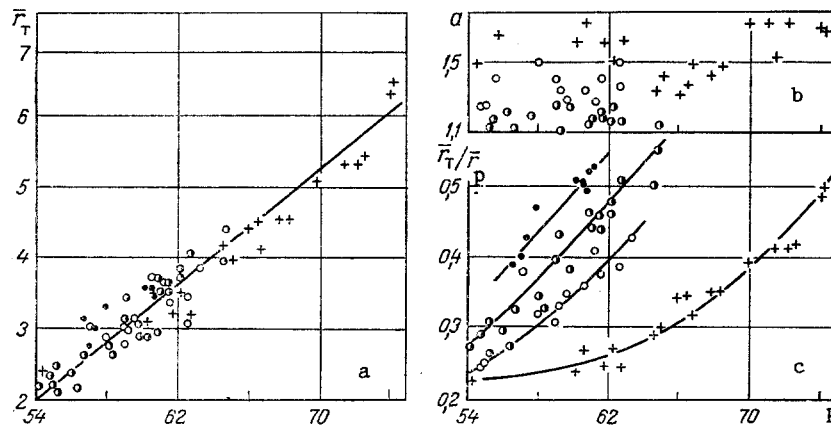


Fig. 4. Dependence of the mean hydraulic pore radius (a), of the coefficient of sinuosity (b), and of the ratio of the mean hydraulic pore radius to the mean radius of powder particles (c) on the total porosity of CPM of titanium powders with different particle size distribution. r_T , r_p , μm .

efficient a lie within the fairly narrow range 1.12-1.73 for all types of powder. The small scatter of the obtained values of a confirms that highly porous materials have pores with low sinuosity, which, however, increases in proportion to the reduction of porosity and of particle size [5]. On the other hand, with equal porosity, CPM from finer powder is characterized by smaller a . Since the coarsest grain of the 1st type has the broadest spectrum of particle sizes, the porous structure of CPM obtained on its basis is less uniform than the others.

In analyzing the data on the coefficient of sinuosity, we note: there is only a small difference between the true pore sizes and the sizes calculated by (4), which is determined by the adopted assumption that $a = 1$ and finds expression in a lowered value obtained for r_T , because the coefficient a calculated by formula (6) is relatively small. In the entire range of porosities we can pinpoint for each powder its own, fairly narrow range of change of the coefficient of sinuosity. For instance, for powder of the 1st type, a fluctuates within the limits 1.33-1.73, and for powder of the 3rd type within the limits 1.12-1.27.

Interesting is also the question of the ratio of the pore sizes of materials to the particle sizes of the initial powder. Such a ratio has the simplest form for materials made from spherical or round particles; it is expressed by the Kozeni dependence. When the shape of the particles differs substantially from spherical shape, the picture becomes more complex. This leads to the mean pore size becoming smaller than the size calculated by the Kozeni formula, and this is also what happens in this case. Figure 4c shows the experimental results of determining the ratio r_T/r_p in dependence on the total porosity P . The values of r_T/r_p in specimens with the same porosity but with different grain size distribution differ substantially.

For each type of powder the dependence of r_T/r_p on P can be described by its own curve, and with increasing mean particle size the ratio r_T/r_p has a tendency to decrease. This fact can apparently be explained as follows: as r_p increases, the scatter of particle sizes in the powder increases (see Fig. 1), and the capillary structure is built up in such a way that small particles fill the pores between large particles. Powder of the 4th type was obtained by screening the large particles on a screen 0040, and it is closer to being monodisperse than the other powders. Its structure is therefore uniform, and the effect of filling large pores is less strongly expressed in it than, e.g., in powder of the 1st type. Similar effects were also noted in [5, 9, 10]. Altogether in the entire range of porosities the ratio r_T/r_p changes from 0.22 to 0.55.

In conclusion it should be pointed out that for the investigated CPM, made by the same technology and from titanium powders with similar mean particle sizes, all the basic structural properties r_M , r_T , K , P_0 depend first and foremost on the total porosity of the material.

NOTATION

P , total porosity; P_0 , open porosity; r_M , maximal pore radius; K , coefficient of permeability; r_T , mean hydraulic pore radius; a , coefficient of sinuosity; r_p , mean equivalent particle radius; D , equivalent particle diameter; M , percent content of fraction on the distribution curve.

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EVAPORATIVE LOSS OF CRYOGENIC LIQUIDS DURING VIBRATION AND TRANSPORT IN VESSELS AND CISTERNS

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It is shown that the cause of increased evaporative loss of cryogenic liquids during transportation is scattering of oscillation energy within the liquid. The dependence of the increase in loss on oscillation parameters and transportation conditions is determined.

When cryogenic vessels and cisterns are transported the rate of cryogenic liquid evaporation is several times greater than under steady-state conditions, for example, 3-8 times greater for liquid helium in a 10-liter vessel [1]. The causes and principles of this increased loss have yet to be studied thoroughly. In [2] experiments were performed involving vibration of a 5-liter liquid helium vessel, and it was found that the increase in loss depended quadratically on vibration amplitude.

The problem of the interaction between an oscillating body and a liquid is quite complex and has been studied by many researchers. A quite complete theoretical analysis of the perturbed motion of a body containing liquid in cavities, with consideration of the liquid's viscosity, was presented in [3]. As the body oscillates, energy is partially scattered in the liquid. The oscillation energy scattering is characterized by an absorption coefficient ψ_0 :

$$\psi_0 = \Delta E/E. \quad (1)$$

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