COPPER SINTERED POWDER WICK STRUCTURES OF MINIATURE HEAT PIPES

Leonard L. Vasiliev, Andrei G. Kulakov, Olga S. Filatova, Sergei V. Epifanov

Laboratory of Porous Media
Luikov Heat & Mass Transfer Institute, National Academy of Sciences,
P. Brovka, 15, 220072, Minsk, Belarus
Phone/Fax: (375-17) 284-21-33; E-mail: Lvasil@hmti.ac.by

Abstract

In the issue of accomplished systematized investigation structural and capillary-transport characteristics of regular and non-regular capillary-porous structures are determined. Structures was made by sintering of free-loaded powder of dendritic and rounded shapes of different fractions of wide range particle sizes, which have come into common use in miniature heat pipes. Empirical dependences for calculating of capillary-porous structure properties are obtained. The dependences state relations between shape, average size of powder particles, capillary-porous structure thickness and other structural and capillary-transport characteristics.

KEYWORDS

Capillary-porous structure (CPS), wick, pore size, porosity, permeability, capillary potential, miniature heat pipe (MHP).

INTRODUCTION

To maintain thermal conditions of electronic equipment is very important for its high performance operation [1, 2]. The problems of thermal conditions optimizing of electronic equipment with an utilizing of dissipated heat can be solved by using heat pipes (HP) – the devices of high effective thermal conductivity. Traditional cooling methods with circulating water or fan air flow often is not feasible because of the need to use advanced heat spreading surfaces many times larger than area of heat source to remove high heat fluxes. Heat pipes are capable to transport high heat fluxes at small temperature differences owing to high values of heat transfer coefficient.

Thermal management problem of electronics objects is coming more and more actual due to growing electronics miniaturization and growing of heat dissipation density. That is why now there is a tendency to miniaturizing of heat pipes [2,3].

Using MHP in thermal management systems of electronics is possible to solve next: to provide heat transfer, heating and cooling of different objects, to provide spatial separation of heat source and heat sink, to level the surface temperature, to provide isothermal heat supply (removal), to realize objects thermo stating, to transform heat flux, to provide thermal management of equipment, to use HP as a thermal diode.

There is no common definition of miniature heat pipes. As a rule, miniature heat pipes are heat pipes, in which vapor channel dimension is comparable with liquid curvature radius in such channel. Usually these are cylindrical or flat HP of diameter or thickness of 1-6 mm. Cylindrical MHP with diameter of 4 mm and flat HP with thickness of about 2 mm are the most wide used at present.

MHP are at the intermediate position between HP of “usual” dimension and so called micro heat pipes. But in scientific publications there is no precise differentiation between definitions of mini and micro heat pipes. By summarizing information about constructional features of such HP next classification can be proposed, using comparison of less dimension of vapor channel cross-section and liquid meniscus curvature radius in CPS to the liquid capillary constant (Table 1). Micro heat pipes are heat pipes, in which liquid meniscus radius ***in CPS*** is comparable with equivalent dimension of vapor channel, more precisely, with less dimension of cross-section. Miniature heat pipes are heat pipes, in which equivalent dimension of vapor channel (less dimension of cross-section for flat plate heat pipes) is comparable with the liquid capillary constant.

Table 1. Heat pipes classification

micro HP	mini HP	HP of "usual" dimension
$r_c \leq \boldsymbol{d_v} < l_c$	$r_c < \boldsymbol{d_v} \leq l_c$	$r_c < l_c < \boldsymbol{d_v}$

In the table: r_c – effective liquid meniscus radius in CPS, d_v – lesser dimension of vapor channel cross-section, l_c –capillary constant of fluid:

$$l_c = \sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}}\ , \tag{1}$$

where σ – surface-tension, g – gravitation constant, ρ_l, ρ_v – density of liquid and gas.

It should be noted that there are peculiarities of heat transfer processes in MHP, which are caused by miniaturization. MHP have a number of characteristic properties like a small cross-section area and therefore high level of non-regularity of wick structure, relatively high hydraulic resistance of vapor channel comparing with usual HP etc. Additionally, interaction of liquid and gas phase of working fluid should be taken into account in MHP.

PECULIARITIES OF SINTERED POWDER WICK STRUCTURES, WHICH APPLIED IN MHP

Non-regular CPS with thickness of about 0.5-1 mm are usually used in MHP. The high level of non-regularity is one of the most important differences from usual HP.

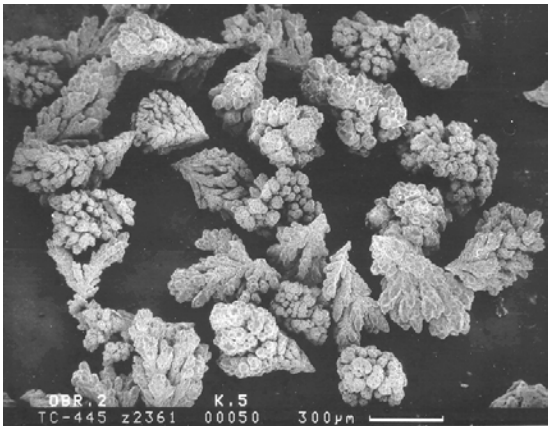
In the result of reference analysis it is clear that due to decreasing of dimensions and growing heat dissipation of electronics, spreading of MHP application area, requirements to MHP are increasing steadily, at first for the maximum performance (heat flux), operational possibility at any spatial orientation, and for stability of characteristics. But existing industrial MHP are not more capable to satisfy the growing practical requirements of MHP application. Performing of effective CPS is one of the ways of MHP improvement.

CPS is the main element of HP. Since its properties determine characteristics of HP, many papers of researchers, e.g. [4-6], are devoted to capillary-transport properties of CPS studying and methods of its calculating, appropriate standards are adopted [7-9].

For sintered powder CPS manufacture different methods of formation which can be divided into two basic groups are used: methods with and without an application of pressure. The most simple, technological and cost-effective sintering mode of powder CPS is the method when powder is free- loaded in the container [10]. This method allows getting more high porosity of CPS, and it basically is applied at manufacture of CPS for HP and MHP.

The use of the formulas for idealized structure of small balls of appropriate sizes results in mistakes of predicting real sintered structures properties. But there is little experimental data on CPS of free-loaded sintered metal powder properties in available references. So, for example, monograph [13] shows serious error while calculating of CPS permeability of sintered powder using Blake-Kozeni formula at porosity higher than 50% and that this formula cannot be used while calculating of CPS with particles of complicated shapes. Development of MHP, optimization of their parameters demand knowledge of main properties of real sintered metal powder CPS, including shape of particles in a wide range of pore sizes of different fraction of powder.

The analysis of literature and our experimental investigations [12] have shown, that CPS made from a metal powder have some advantages comparing to other types of HP wicks: they are technological, rather inexpensive, have a set of high operation properties and suppose an opportunity of their wide variation, chance sintering of CPS to heat transfer surfaces. However now there are no reliable systematized experimental data related to properties of sintered a metal powder capillary - porous structures, found the widest application in heat pipes and MHP in particular. The most complete information found concerning sintered powder CPS [10] related to only CPS of dendritic shape particles. Therefore comprehensive research has been carried out and both structural and capillary transport characteristics of CPS made from copper sintered powder of dendritic (fig. 1) and round particles are defined.



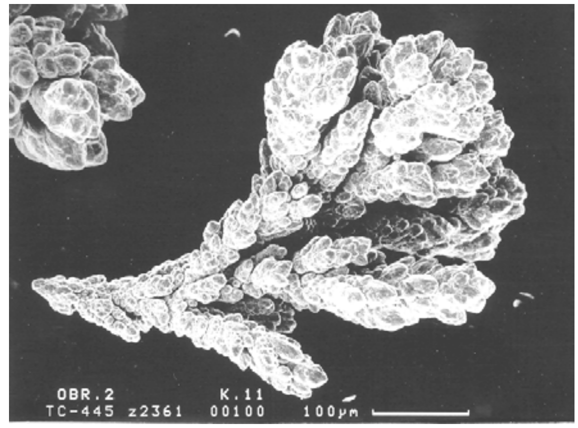


Fig. 1. Copper powder of the dendritic shape obtained by the electrolytic method

EXPERIMENTAL SETUP AND TECHNIQUES FOR CPS PROPERTIES INVESTIGATION

Special experimental setup was implemented for the investigation of structural and capillary-transport characteristics of the porous structures (fig. 2). It consists of following main elements: source (container) of compressed air (1), pneumatic circuit with flow meter (4) and air pressure gages (6, 7), and also special holder – device for mounting of samples. The last one consists of the case, rubber seals, centering and compression rims and twisting clamp cover with the orifice.

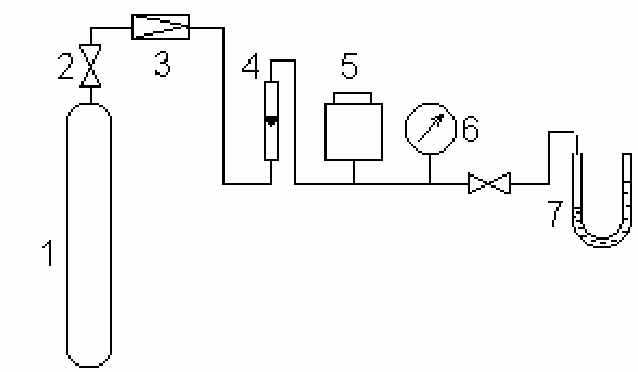


Fig. 2. Experimental setup for CPS properties investigation: 1 – container with compressed air, 2 – valve, 3 – reducer, 4 – flow meter, 5 – holder with sample, 6 – manometer, 7 – U-shaped manometer.

CPS properties (porosity, effective pore diameters, permeability) determination was made under the requirements of state standards [7-9].

Sintered of copper powder cylindrical samples of CPS with diameter about 30 mm and thickness of 0.5 to 15 mm were investigated. To improve the reliability of results obtained several samples of each size were made for each fraction.

Porosity evaluation

After the weighting using electronic automatic balance porous sample was wetted with distilled water in vacuum until the maximum saturation of all pores, and porosity was calculated by:

$$\varepsilon = \frac{\rho_m (m_w - m_m)}{\rho_l m_m + \rho_m (m_w - m_m)}, \tag{2}$$

where ε – porosity, ρ_l, ρ_m – density of liquid and metal, m_m – dry sample mass, m_w – wetted sample mass.

Pore size evaluation

Using this method pressure for bubbling of the first (2-3) bubble on the surface of the liquid wetted sample was measured to determine the maximum pore size. To determine average pore size pressure for bubbling from all surface of the sample was measured. Pore diameter was calculated:

$$d=4\sigma_l cos\theta/\Delta p, \qquad (3)$$

where σ – surface-tension, θ - wetting angle, $\Delta p=\Delta p_a-\rho gh$ – pressure drop on the sample, Δp_a – air pressure under the sample measured by manometers, ρgh – hydrostatic pressure drop of the liquid above the sample. In the case of perfect wetting $\cos\theta=1$.

The samples were wetted completely by a liquid to investigate maximum pore size and average pore size of CPS. Liquid level of definite thickness was poured on the sample surface. Isopropanol was used as a testing liquid. Imbibition of the samples by the liquid was made in vacuum.

The liquid wetted sample of the CPS studying was mounted in special holder described above. Temperature of the liquid was measured by the standard thermometer. Under the studying sample smooth increasing of gas pressure was being carried out.

Pressure of first bubble displacement was fixed at occurrence of a jet (or 2-3 jets) of air bubbles on a surface of a sample. The measured pressure p_{min} corresponded to value of the biggest pores in a sample. At further pressure rising the value corresponding to air bubbles removing on all surface of a sample was fixed.

Permeability coefficient evaluation

For definition of coefficient of permeability samples were not imbued with a fluid. The gas of known viscosity and a density passed through a tested porous sample with measuring pressure drop and flow rate.

Pressure of gas (air) under a sample smoothly rises, at the same time flow rate of gas V and appropriate pressure drop Δp are monitored. Using obtained values the coefficient of permeability is defined as

$$K=\frac{\mu\delta_{cs}V}{\Delta pA}, \qquad (4)$$

where A - a cross-sectional area of a sample, μ – dynamic viscosity, δ_{cs} – thickness of CPS, $\Delta p = \Delta p_1 - \Delta p_2$ - difference between the measured pressure drop on a sample Δp_1 and before measured pressure drop Δp_2 in holder without a sample at the same values of flow rate. Thus the requirement $\Delta p_2 << 0.1\Delta p_1$ should be satisfied.

Features of the CPS properties experimental research

It is necessary to remark, that there is some subjectivity in definition of the mean sizes of pores by the method of displacement of wetting fluid from pores via gas since for uniform bubbles removing on surface of a sample there corresponds rather wide range of gas flow rates and pressure drops. Therefore in the experiments pores sizes d_{ch}, related *to the beginning of the uniform* air bubbles appearance on all surface of a sample, and the sizes of pores d_m, corresponding *to the beginning of intensive bubbling* (at changing flow rate minor deviation of pressure drop is observed) were defined separately. Flow meter in addition was used for more precise definition of the moment of reaching of pressure related to the mean pores size.

Characteristic size of pores d_{ch}, characterizes capillary potential of CPS in heat pipes of traditional construction, because of it corresponds to an essential degree of drying of porous structure. It should be used as effective size at calculation of capillary potential in “usual” HP. Hydraulic size d_h is applied usually for CPS permeability calculations. The mean size of pores d_m, with tortuosity coefficient can be used at calculation of hydraulic resistance of CPS and it is used usually for capillary potential of HP wick definition. The maximum size of pores d_{max} corresponds to capillary potential of CPS in CPL (LHP), evaporators and condensers with the capillary - porous structure executing function of capillary gate.

PROPERTIES OF REGULAR SINTERED POWDER CAPILLARY - POROUS STRUCTURES

Developing heat pipes or MHPs for choice of corresponding fraction of metal powder it is necessary to know dependence of the capillary pressure created by CPS and its permeability vs. the size of powder particles. Such dependences have been obtained experimentally for different fractions of copper sintered powder CPS in a range of the mean-weighted size of particles 20-240 microns [13,14].

Based on experimental data approximating dependences of effective pore size from mean-weighted size of particles in a fraction were obtained (shown in tab. 2):

$$d_s = d_{s,\min} d_{s,\max} \sqrt{\frac{2}{d_{s,\min}^2 + d_{s,\max}^2}} . \tag{5}$$

In the eq. 5 $d_{s,min}$ and $d_{s,max}$ - minimal and maximal sizes of particles in fraction

Table 2. The effective sizes of pores experimental data

Round shape particles	Dendritic shape particles	
	d_s<120 microns	$d_s \geq 120$ microns
$d_{\max} = 5.47 \cdot 10^{-3} d_s^{0.528}$	$d_{\max} = 3.09 \cdot 10^{-3} d_s^{0.438}$	$d_{\max} = 0.132 d_s^{0.85}$
$d_{ch} = 5.5 \cdot 10^{-3} d_s^{0.539}$	$d_{ch} = 2.31 \cdot 10^{-3} d_s^{0.42}$	$d_{ch} = 0.116 d_s^{0.85}$
$d_m = 8.85 \cdot 10^{-3} d_s^{0.61}$	$d_m = 6.7 \cdot 10^{-4} d_s^{0.315}$	$d_m = 0.315 d_s^{0.996}$
$d_h = 0.004 d_s^{0.55}$	$d_h = 0.0056 d_s^{0.55}$	

Permeability coefficient of CPS can be evaluated with dependence of Hagen - Darcy

$$K = \frac{d_h^2 \varepsilon}{32} , \tag{6}$$

using experimental data (tab. 2) where ε is porosity of CPS. ε=0.65 for dendritic shape and 0.55 - for round shape of CPS particles.

The mean hydraulic size of CPS pores d_h was defined with Hagen - Darcy formula from experimental permeability K and porosity ε data.

$$d_h = 5.66 \sqrt{K / \varepsilon} . \tag{7}$$

The capillary pressure created by CPS is defined as

$$\Delta p_c = \frac{4\sigma \cos\theta}{d_{ch}} = \frac{4\sigma \cos\theta}{c_1 d_s^{c_2}} , \tag{8}$$

where c_1 and c_2 - the relevant coefficients (from tab. 2).

Experimental research allows recommending for using as an initial powder of CPS particles of the dendritic shape, having the best mass transfer properties at transportation of working fluid in heat pipes.

Thus, CPS, obtained by sintered free - loaded powder at optimum temperature of sintering, is completely characterized by the shape and size of powder particles. There is the unique functional interdependence between the shape, the size of powder particles and structural and capillary - transport characteristics of CPS.

More detailed analysis of experimental results of investigations of regular CPS properties is done in [13].

NON-REGULAR SINTERED POWDER CPS PROPERTIES

Capillary-porous wicks of MHPs, as a rule, practically always are non-regular. Therefore at calculating of capillary - transport characteristics it is necessary to take into accounting a degree of irregularity of porous structure.

Pore size distribution functions are differ for thick and thin porous structures**.** Non-regular CPS is thin CPS, capillary properties (pore size distribution) of which are differ from CPS properties of big width made from a powder of the same fraction. Level of irregularity of a structure is the coefficient of regularity [4].

There is some critical width of a porous layer when the porous structure becomes the regular. With diminution of width of a porous layer irregularity of CPS is augmented, diameter of pores and porosity increases. The coefficient of regularity firstly entered by Kostornov [4] is defined as a ratio of the equilibrium maximum size of pores of the regular structure to the maximum size of CPS pores of the given width:

$$C_{cs}= d_{max}/d_{ir,max}, \quad . \tag{9}$$

where $d_{r,\ max}$ - is the maximum size of pores of the regular structure, $d_{ir,\ max}$ – is the maximum pore size of non-regular structure.

There are a few articles concerning investigations of properties of non-regular CPS. Most of them are about metal felts properties [4, 15]. And there are practically unique article regarding non-regular sintered powder CPS. Results of experimental study of maximum pores size from width dependence of non-regular CPS made from bronze sintered round powder were only detected in literature, and formula for definition of regularity coefficient is presented in [16].

$$C_{cs}=(n_{ir}/24)^{0.282} , \tag{10}$$

where $n_{ir}=\delta_{cs}/d_s$ - number of particles along width of non-regular structure.

In [17] the theoretical analysis of influence of CPS regularity to maximum heat transfer rate of heat pipes and HP thermal resistance is executed. In that work data [16] were used in calculations.

Despite of enough wide spreading, available structural and capillary - transport properties data of sintered powder CPS restricted and inconsistent, and properties of non-regular CPS are the least investigated.

Thus, at present researches of non-regular sintered powder structures properties restricted only the maximum diameter of pores from width dependence for bronze particles of round shape. Other parameters of non-regular sintered powder CPS data are not revealed in the literature. Therefore the systematized examinations of properties of non-regular sintered powder structures have been carried out. In fig. 3 the typical data - porosity of CPS vs. its width, and in fig. 4 - the typical dependences for the sizes of pores are shown.

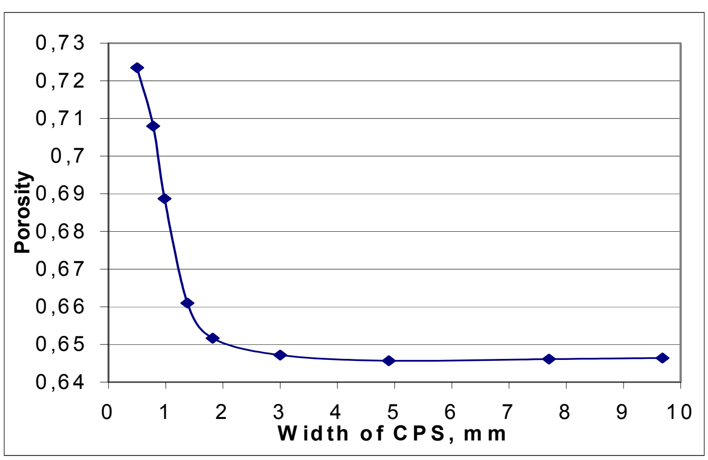


Fig. 3. Porosity of sintered powder CPS vs. width of layer; fraction 200-315 microns, the dendritic shape of particles

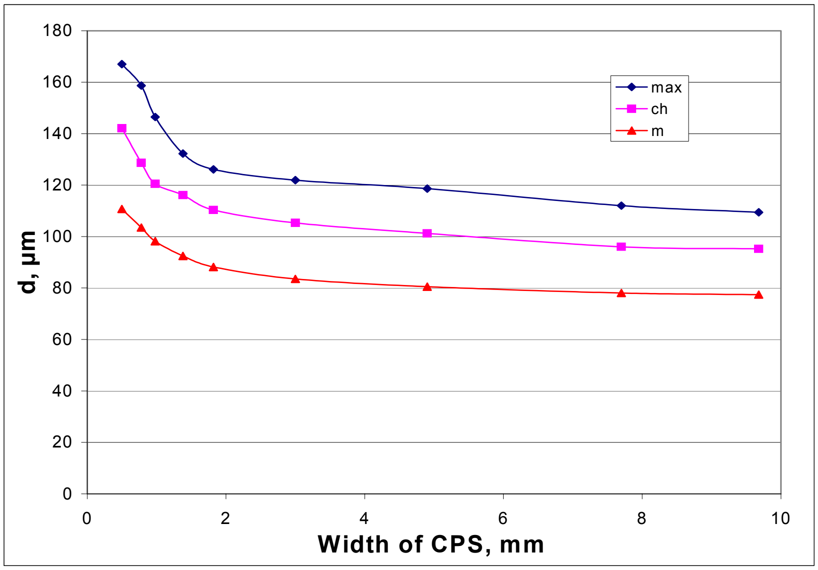


Fig. 4. Pores size of powder CPS d depending vs. width of layer; fraction 200-315 microns, the dendritic shape of particles; max – maximum, ch - characteristic and m – mean sizes of pores

As a result of investigation it is established, that properties of non-regular CPS, obtained by sintering of free - loaded powder, are uniquely characterized by its width, shape and size of powder particles, but character of dependence of maximum diameter of pores and other structural characteristics (for example, porosity) from width not always submits to one regularity, i.e. coefficients of regularity for them do not coincide. Therefore individual coefficients for effective characteristics of CPS, for round and dendritic shapes of particles have been obtained.

For calculation of non-regular CPS characteristics the empirical dependences between the shape, the mean-weighted size of powder particles, width of CPS and other structural and capillary - transport characteristics are obtained. Formula for calculation of permeability coefficient of non-regular structure is:

$$K = \frac{d_h^2 \varepsilon}{32} \left(\frac{n_r}{\delta_{cs} / d_s} \right)^{2m} \left(\frac{n_{r\varepsilon}}{\delta_{cs} / d_s} \right)^{m_{re}} . \tag{11}$$

Equation for calculation of capillary pressure of non-regular CPS is:

$$\Delta p_c = \frac{4\sigma \cos\theta}{d_{ir,ch}} = \frac{4\sigma \cos\theta}{d_{ch} \left(n_r d_s / \delta_{cs} \right)^m} . \tag{12}$$

In the formulas d_{ch} – pore size of regular CPS (tab 2.), n_r, m, $n_{r\varepsilon}$, m_ε, – coefficients from tab. 3.

Table 3

Empirical coefficients for calculation of non-regular CPS characteristics

	d_m, d_h,	d_{max}, d_{ch}	ε	
CPS made from a powder of round shape particles				
m	0.28		m_ε	0.28
n_r	18	24	$n_{r\varepsilon}$	6
CPS made from a powder of dendritic shape particles				
m	0.15		m_ε	0.11
n_r	24		$n_{r\varepsilon}$	6

The empirical coefficients (tab. 3) used in the formulas are obtained as a result of experimental data analysis of dependences of properties CPS from width of a structure.

CONCLUSIONS

1. Between mean-weighted sizes of particles and other parameters of the regular CPS, obtained via sintering of free - loaded powder at optimum temperature of sintering, the unique functional correlation exists. Structural and capillary - transport characteristics can be expressed directly through the mean-weighted size of particles. Empirical dependences for calculation of these characteristics are obtained taking into account the shape of powder particles.
2. Different character of dependence of the maximum pore diameters and other structural characteristics of non-regular CPS from width was detected; the relevant individual empirical coefficients for their calculation are obtained.
3. Properties of non-regular CPS, obtained via sintering of free-loaded powder, uniquely are characterized by its width, shape and size of particles of a powder. For calculation of capillary - transport characteristics of non-regular CPS the empirical dependences between width CPS, the shape, the mean-weighted size of powder particles and other structural and capillary - transport characteristics are obtained.
4. Experimental researches allow recommending to use the particles of the dendritic shape as an initial powder for manufacture of CPS in MHP, having the best mass transfer properties at transportation of working fluid in heat pipes.

References

1. Reznicov G.V. *Calculating and designing of cooling systems of computers*. M.: Radio i sviaz, 1988. 224 Pp. (In Russian).
2. Groll M., Schneider M., Sartre V., Zaghdoudi M.C., Lallemand M. Thermal control of electronic equipment by heat pipes // *Rev. Cen. Therm*. 1998. – 37. Pp. 323-352.
3. *Proceedings of 13th International Heat Pipe Conf.* / Shanghai, China, September 21-25, 2004.
4. Kostornov A.G. *Permeable metal felt materials.* Kiev: Technique, 1983. 123 p. (In Russian).
5. Vitiaz P.A, Kaptsevich V.M., Sheleg V.K. *Porous powder materials and workpieces from them.* Minsk.: Vysheishaia shkola, 1987 (In Russian).
6. Belov S.V. *Porous metals in industry.* M.: Mashinostrroenie, 1981. 247 p. (In Russian).
7. GOST 26849-86 Materials made from sintered powder. Method of pores size definition (In Russian).
8. GOST 25283-93 Materials sintered permeable. Definition of permeability of fluids (In Russian).
9. GOST 18898-89 Articles made from powder. Methods of density definition, content of oil and porosity (In Russian).
10. Maziuk V.V. *Calculation and heat transfer rate optimization of powder capillary structures of low temperature heat pipes.* PhD. Thesis. Minsk, 1990. 118 p. (In Russian).
11. Vasiliev L.L., Konev S.V., Khrolenok V.V. *Intensification of heat transfer in heat pipes.* Minsk: Nauka I Tekhnika, 1983 (In Russian).
12. Vasiliev L.L., Maziuk V.V., Kulakov A.G., Rabetsky M.I., Vukovic M. Miniature heat-pipe thermal performance prediction tool - software Development // *J. Applied Thermal Engineering.* 2001. Vol. 21. Pp. 559-571.
13. Kulakov A.G. *Intensification of heat and mass transfer in evaporation - condensation devices of two-phase thermal management systems.* PhD. Thesis. 2005. 178 p. (In Russian).
14. Vasiliev L.L., Kulakov A.G. Features of heat and mass transfer processes in miniature heat pipes // *Bulletin GGTU im. P.O.Suhogo*, 2005. № 2. Pp. 15-23 (In Russian).
15. Kostornov A.G. Parameters of porous structure permeable felt materials. Theoretical preconditions and modelling researches // *Powder metallurgy.* 1978, № 4. Pp. 34-40 (In Russian).
16. Todorov R.P., Georgiev V.P., Vitiaz P.A., etc. The regularity of structure of porous materials made from powder bronze // *Powder metallurgy.* 1986, № 3. Pp. 31-33 (In Russian).
17. Maziuk V.V., Rak A.L., Balashchenko A.V. Heat and mass transfer at evaporation from thin layers of powder capillary - porous structures // *Proceedings of 5th Minsk International Heat And Mass Transfer Forum MIF-2004*, 24-28 May, 2004, Luikov Heat & Mass Transfer Inst. Minsk, Belarus, 2004, Paper 7-22 CD ROM / HMTI Minsk, 2004 8 p. (in Russian).