STRUCTURAL, THERMOPHYSICAL AND MECHANICAL CHARACTERISTICS OF METAL FELT WICKS OF MODERN HEAT PIPES

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ABSTRACT

The article reflects the results of many years’ researches, begun in 1972, of structural, hydrodynamic, thermophysical and mechanical properties of metal felt capillary structures (MFCSs) of heat pipes (HPs). These structures were made from the discrete sintered fibres with length 0.002-0.01 m by a diameter from 20 µm to 70 µm of a copper, stainless steel, or nickel. They were intended for HPs with shells of a copper, stainless steel, nickel, titan, nickel silver, ceramics and heat carriers: nitrogen, ammonia, water, ethanol, methanol, acetone, sodium and others. HPs worked in the range of temperatures from a cryogenic level (-190 ^{o}C) to high temperatures (+ 800 ^{o}C). Analytical and experimental researches are executed by authors from the National Technical University of Ukraine “Kyiv Polytechnic Institute” (Kyiv, Ukraine) under the leadership of Dr., Prof. Semena M. On the basis of the conducted researches the functional dependences are obtained for implementation into engineering calculations of heat transfer characteristics of HPs. The proposed methods of the rational HP design with the use of MFCSs and elaborated technology of their fabrication allowed to create and implement into practice a variety of heat pipes and systems on their basis for different fields of application.

KEY WORDS: heat pipe, metal fibres, capillary structure, characteristics

1. INTRODUCTION

Application of MFCSs as capillary structures (CSs) of HPs allows creating of such designs of HPs, which are often impossible to realize on the basis of other types of CSs (from metallic screens, powders, grooves and others). It is especially important at making some specific demands on HPs: operation against gravity, necessity of applying of CS to the surfaces of complex shape, necessity of deformation of HP after its fabrication and others.

Advantages of CS from discrete metal fibres over other types of CS are conditioned by a number of their unique properties. So, MFCSs have a very wide range of effective porosity: from 0.5 (and less, if necessary) to 0.96 (and higher). They are characterized by the wide range of diameters of pores: from minimum (5 µm and less) to maximal (300 µm and more), and have no closed pores (fig. 1). This allows to reach the optimum combination of basic hydraulic characteristics of MFCS, namely, high coefficient of permeability and high available capillary head.

Optimum hydraulic characteristics of MFCSs in combination with their high enough frame heat conductivity (from 0.5 to 50 W/mK) provide high-efficient heat engineering characteristics of HPs: low thermal resistance R_{hp} and high maximal heat transfer ability Q_{max}.

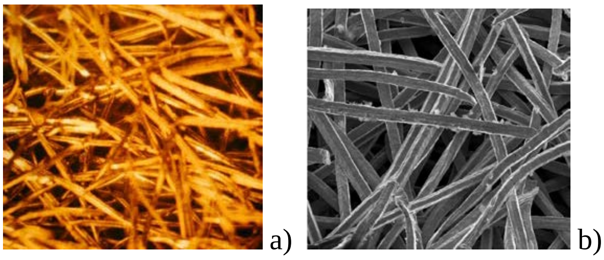
a) b)

Figure 1: Appearance of metal felt capillary structures (magnification in 75 times): fibres from a copper by a diameter of 20 µm (a), from stainless steel, 30 µm (b).

For example, for low temperature HPs the values of R_{hp} are, as a rule, within the range (0.03 – 0.3) K/W, and the value of Q_{max} makes tens watts during operation against gravity and hundreds watts – in the absence of its influence. It is possible to find in-depth information about characteristics of HPs with MFCS and results of their practical application in work [Semena et al., 1984], and additional information about properties of metal felt materials – in work [Kostornov, 2002].

2. RESEARCH OF STRUCTURAL CHARACTERISTICS OF MFCS

Among initial structural characteristics of MFCS there are the following: diameter of fibre d_f, length of fibre l_f, average porosity ε, maximal D_{max}, middle (effective) D_{mid} and minimum D_{min} diameters of pores, and also pore size distribution.

Usually for HPs application the discrete fibres by a diameter from 20 μm to 50 μm are used, and lately, ultrafine fibres from 4 μm to 18 μm. The length of separate fibre is from 0.001 to 0.003 m (and more, if necessary). Average volume porosity of CS is within the range from 0.6 to 0.96, and at the use of micro fibres one can attain extremely high porosity from 0.98 to 0.995 [Adkins et al., 1994]. Obtainable (maximal) porosity of MFCS can be defined by empiric dependence:

$$\varepsilon_{max} = exp\ (-6\ d_f / l_f). \qquad (1)$$

MFCSs are nonuniform structures, therefore they are characterized by the differential or integral (cumulative) pore size distribution (fig. 2).

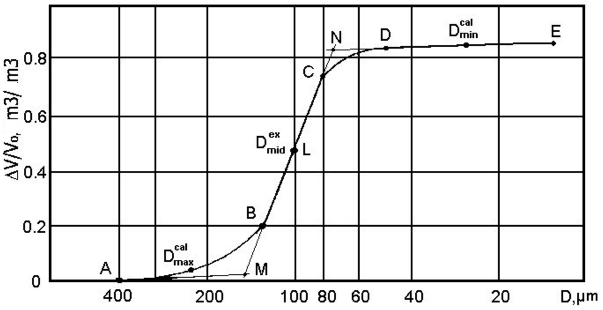

Figure 2: Curve of cumulative distribution of relative volume of pores over pore diameters. Volume porosity ε = 0.85, d_f = 30 μm, l_f = 0.003 m

Such distributions can be obtained by mercury intrusion porometry. From cumulative distribution curves it is possible to extract information about the maximal, middle and minimum sizes of pores (fig. 2). Typical ranges of sizes of MFCS pores: D_{max} = 50 – 300 μm; D_{mid} = 20 – 150 μm; D_{min} = 5 – 50 μm.

More correct values of sizes of MFCS pores (especially, high-porous) are obtained by other methods of their determination: method of gas permeability in combination with the model of ideal porous medium and method of extruding of liquid from pores (method of Barus-Bechgold). On the basis of processing of experimental data, got by the indicated methods, authors obtained the following dependences for calculations of MFCS parameters.

$$\begin{aligned} D_{max} &= d_f^{0.7} l_f^{0.3} \varepsilon^2 \left(1-\varepsilon\right)^{-0.5}; \\ D_{mid} &= 0.4 d_f^{0.7} l_f^{0.3} \varepsilon^{1.6} \left(1-\varepsilon\right)^{-0.5} \qquad (2) \\ D_{min} &= 0.1 d_f^{0.7} l_f^{0.3} \varepsilon \left(1-\varepsilon\right)^{-0.5}. \end{aligned}$$

3. HYDRODYNAMIC CHARACTERISTICS OF MFCS

The considered structural characteristics of MFCS determine capillary-transport properties: capillary pressure ΔP_{cap}, coefficients of liquid permeability K_1 and K_2 (permeability at liquid movement in two orthogonal directions), limiting wetting angle, characteristics of capillary absorption of heat carrier into the dry structure. Hydrodynamic characteristics of MFCS were investigated on samples with porosity from 0.58 to 0.96, from copper and stainless steel fibres by a diameter of 20, 30, 40, 55 and 70 μm, and the length of 3 mm, with water, acetone, ethanol and benzyl alcohol as workings fluids. As a result of experimental data processing and modelling authors have obtained the following dependences:

- for determination of capillary pressure:

$$\Delta P_{cap} = 35 \sigma\, cos\, \theta (1-\varepsilon) d_f^{-1} \sqrt{1-\varepsilon_{max}}\,, \qquad (3)$$

- for determination of permeability across the axis of fibres (across the plane of felting):

$$K_1 = \frac{d_f^2}{16} \left(\frac{1-\varepsilon}{1+\left(1-\varepsilon\right)^2} - \frac{1+\ln\left(1-\varepsilon\right)}{2\left(1-\varepsilon\right)} \right) \left(\frac{1-\varepsilon}{1-\varepsilon_{\max}} \right)^2 \bullet$$

$$\exp\left(-1.45(1-\varepsilon)\left(1-\varepsilon_{\max}\right)^{0,7}\right), \qquad (4)$$

- for determination of permeability along the axis of fibres (along the plane of felting):

$$K_2 = 0.0043 (D_{mid})^2 / (1-\varepsilon). \qquad (5)$$

On figure 3 the generalizing dependences of coefficients of MFCS liquid permeability with the diameter of fibres of 30 μm (curves 1 and 2) and 55 μm (curves 3 and 4) on porosity, calculated by formula (5) for curves 1 and 3 and by formula (4) for curves 2 and 4 are resulted.

Coefficients of MFCS permeability across and along fibres are approximately identical in the wide enough range of porosity, up to the value $\varepsilon/\varepsilon_{max} \approx 0.9$. It is explained by homogeneity and regularity of structure in various directions. In MFCSs the volume porosity of which is approached to maximally possible, the isotropy of their structure is violated, and permeability in direction along fibres considerably exceeds permeability across fibres.

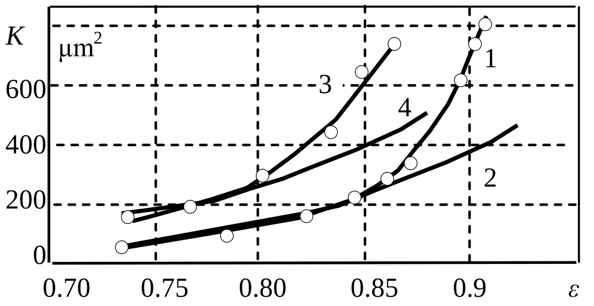

Figure 3: Dependences of coefficient of MFCS liquid permeability on volume porosity, diameter of fibres and direction of liquid filtration.

Limiting angle of wetting Θ of metals with liquids, as a rule, differs from ideal, that results in diminishing of values of capillary pressure and, accordingly, maximal heat flux, transferred by HP. According to authors' data the values of Θ, measured by the method of lying drop, for a pair copper-water are 72 ± 2°, for a pair copper – ethanol – 15 ± 5°, and at the use of acetone, methanol, methylal and freons – $\Theta = 0°$. However the use of method of the capillary rise of liquid in dry MFCS gives other results: copper fibres - acetone – 41 ± 2°, stainless steel fibres - acetone – 39.5°, copper - ethyl alcohol – 45 ± 1°, copper – ethanol – 40 ± 1°, and water in general is not absorbed in dry MFCS. Thermal oxidation of CS from the fibres of copper, steel, and nickel sharply improves their wettability with organic heat carriers, practically to $\Theta = 0°$, and with water – to 8 – 13°.

Results of researches of the available capillary pressure of ΔP_{cap}, coefficients of permeability K_1 and K_2 and limiting wetting angles Θ were approved and confirmed at the study of characteristics of capillary absorption organic liquids and water into the dry MFCS samples as plates 0.5 m long, 0.045 m wide and 0.002 m thick. Porosity of samples was within the range from 0.61 to 0.95, material of fibres was copper and stainless steel, their diameter – 20, 30, 40 and 70 μm. The conducted researches have shown a high capillary-transport ability of MFCS not only at horizontal orientation but also at operation against gravity. Rate of saturation of MFCS with working fluids was found far above, than of CS from screens and fabrics.

4. HEAT CONDUCTIVITY OF MFCS

Experimental data on heat conductivity of MFCS available in references differ considerably from the results of calculations by the theoretical and semi-empiric formulas of heat conductivity of porous bodies. It is explained, mainly, by absence of consideration of thermal resistance of heat conductivity of contacts between dispersible discrete elements forming a porous structure. Technology of MFCS fabrication, including the processes of pressing and sintering, provides a good thermal contact between separate fibres. However, as follows from the results of metallographic analysis, nevertheless, contacts are not ideal. Equivalent diameter of spot of contact between the sintered fibres is less than fibre diameter, i.e. ratio of these two magnitude (y), as a rule, is within $0 < y \leq 1$. The value of y formed due to the processes of sintering (y_1) and pressing (y_2), can be calculated by dependences, obtained by processing of experimental data:

$$y = y_1 + y_2,;\ y_1 = c\varepsilon^{0.1}(l_f / d_f)^{0.5},\ 0 < y_1 < 1;$$
$$y_2 = (1+c)d_f^{-0,13} - \varepsilon,\quad 0 \leq y_2 < 1, \tag{6}$$

where d_f and l_f are in micrometres, and coefficient c depends on material of fibres and technological parameters; it is equal: for copper 0.031, for stainless steel – 0.05, for nickel – 0.065, for nichrome – 0.08.

For the calculation of effective heat conductivity of porous materials from discrete fibres across a plane of felting authors offer the following analytical dependence:

$$\lambda_{eff} = \lambda_1 \left[(1-\varepsilon)^2 M + \varepsilon^2 \beta + \frac{4\beta\varepsilon(1-\varepsilon)}{1+\beta} \right], \tag{7}$$

where $\beta = \lambda_s/\lambda_1$; λ_s, λ_1 – coefficients of heat conductivity of material of fibres and liquid.

The parameter M takes into account an influence of imperfection of contacts between fibres on heat transfer in contact area:

$$M = y + [2A\sqrt{1-y^2}\left(1-y\right)]/[A\sqrt{1-y^2}+\left(1-y\right)]$$
$$A = \sqrt{\pi}\beta(1-\beta)\left((1-\beta)^{-1}\ln\beta^{-1}-1\right). \quad (8)$$

One can use the same formulas for the calculation of frame heat conductivity of MFCS ($\lambda_s = 0$ and $\beta = \lambda_s/\lambda_1 = 0$).

Figure 4 illustrates the authors' experimental data and data of other researchers as sings, and also curves, calculated by formulas (7) and (8), for effective heat conductivity of MFCS from stainless steel (curve I), nickel (curve II) and copper (curves III – VIII), and namely, for fibres: by diameter of 30 µm, 3 mm long (curve I), 50 µm, 3 mm (curve II), 70 µm, 3 mm (curve III), 40 µm, 3 mm (curve IV), 70 µm, 10 mm (curve V), 20 µm, 3 mm (curve VI), 40 µm, 10 mm (curve VII), 20 µm, 10 mm (curve VIII).

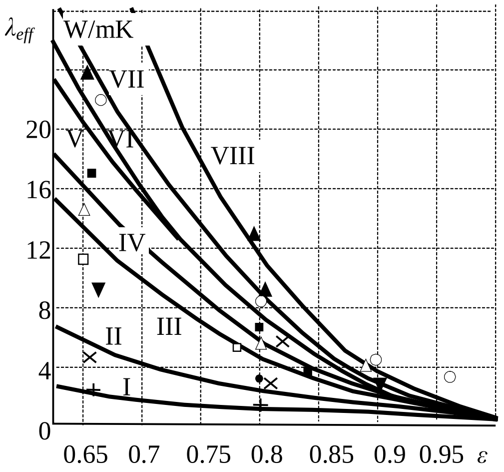

Figure 4: Dependences of coefficients of effective heat conductivity of MFCS saturated with water on porosity.

The increase of CS porosity, shortening of discrete fibres and increase of their diameter reduce both effective and frame heat conductivity of MFCS. Substantial distinction of experimental and calculation data is observed only for CS with porosity close to highest possible, where the structure becomes nonisotropic.

5. RESEARCH OF MECHANICAL PROPERTIES OF MFCS

Except structural, hydrodynamic, thermophysical characteristics of MFCS and their capillary-transport properties, in a number of cases, knowledge of mechanical properties of porous structures is needed, for example, for structures used in full scale solar receivers with sodium as heat carrier.

Authors investigated mechanical properties of CS with porosity from 0.8 to 0.99, thickness from 2 to 5 mm from discrete fibres of stainless steel by a diameter from 4 to 55 µm, 3 mm and 10 mm long. Fibres were sintered with each other and with substrates or dome of receiver of Haynes Alloy 230. Researches were conducted at the temperature of 20 °C and 750 °C on test benches, described in works [Baturkin et al., 2002, 2005].

Dependences of some mechanical properties of MFCS on their porosity ε (a) and relative porosity $\varepsilon/\varepsilon_{max}$ (b) are resulted on figure 5. The values of proportional limit of MFCSs at elongation are substantially reduced not only at the increase of their porosity and decrease of fibre diameter, but also at the rise of temperature of exploitation (reduction approximately in 5 times).

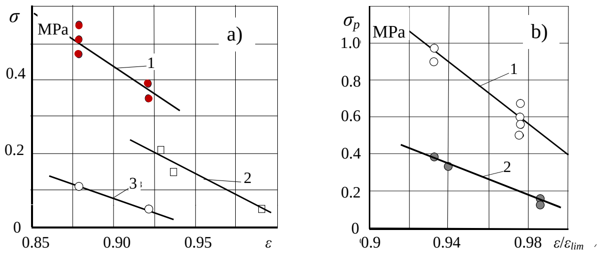

Figure 5: Dependences of proportional limits at elongation of MFCS (a) and pullout forces from substrate (b) on porosity. Lines 1 and 3 – fibre diameter of 30 µm, length 3 mm; line 2 – 8 µm, 10 mm. Temperature of tests: lines 1 and 2 – 20 °C, line 3 – 750 °C.

The proportional limits at the compression of MFCS in the conditions of high temperature (750 °C) have similar dependences and for the structures from fibres with diameter of 8 µm are equal: 2 – 3 kPa (porosity 0.993) and 5 – 7 kPa (0.985), from 30-µm fibres – 13 – 15 kPa (0.9) and 15 – 18 kPa (0.85), from 55-µm fibres – 19 – 20 kPa (0.85) and 22 – 23 kPa (0.82).

The conducted researches confirmed possibility of application of MFCS even for the high temperature heat pipes of large sizes. However not all CS designs were suitable for this application. So structures from ultrafine fibres (by a diameter of 4 and 8 µm) do not possess sufficient mechanical properties, necessary for their using at the temperatures of 800 °C in full scale high temperature solar receivers.

6. APPLICATION OF HEAT PIPES WITH MFCS

The field of application of MFCS in HP is determined by the following features. Technology of fabrication of capillary structures allows to get CS with the given structural parameters, which can be repeatedly reproduced, to realize the reliable fastening and contact of CS with the HP case, to apply CS to the surface of complex shape, and to give possibility to deform the cases with CS to put HP into proper shape.

Hydrodynamic, capillary-transport and thermophysical characteristics and properties of MFCS can be presented by the clear enough functions of initial structural parameters.

Above mentioned advantages are the necessary terms of receipt of reliable functional dependences between the structural parameters of CS and heat mass transfer characteristics of HP, which do not variate during HP operation and allow to conduct their calculations and optimization.

High capillary-transport properties of MFCS in comparison with other types of inserted CS in the conditions of presence or absence of counteractive influence of mass forces are explained by the specific of formation of MFCS, consisting of high limiting porosity, absence of the closed and one-side open pores, and low convolution of pore channels.

Heat pipes with MFCS possess high heat transfer ability and low thermal resistance in the conditions of presence (absence) of counteractive influence of mass forces. On the basis of such CSs a number of HP modifications are created, such as gas regulated heat pipes, thermal diodes, thermal siphons, and loop heat pipes.

7. CONCLUSIONS

The conducted researches of structural, hydrodynamic, thermophysical and mechanical properties of metal felt capillary structures have shown appropriateness of their use as wicks of heat pipes. Technology allows to make HP of any form, to create complex capillary structures with reliable hydraulic and mechanical connection, to attain the reiteration of CS properties, which can be preliminary calculated, to deform the HP case at its mounting without wick damage or its performance degradation.

The aforesaid is confirmed by long experience of application of HPs with MFCS in such fields, as cooling, temperature control and thermostatting of various electronics, cooling of devices of aircrafts, including space vehicles, providing of the thermal conditions of optical, analytical and precision instruments, including lasers, cooling of mechanical and electrotechnical equipment, providing of technological treatment of materials, medical engineering and so forth.

NOMENCLATURE

R_{hp}	heat pipe thermal resistance (K/W)
λ_{eff}	heat conductivity of capillary structure, saturated with liquid (W/(mK)
λ_s/λ_1	ratio of fibre material heat conductivity and liquid conductivity (-)
ε_{max}	maximal obtainable porosity of capillary structure (-)
Q_{max}	maximal heat transfer of heat pipe (W)
l_f	length of fibre (mm, m)
d_f	diameter of fibre (μm, m)
Θ	limiting angle of wetting (grad)
$\Delta V/V$	ratio of volume of pores /to total volume of capillary structure
D	pore diameter (μm, m)
ΔP_{cap}	capillary pressure (N/m^2)
K	liquid permeability of capillary structure, saturated with liquid (m^2, μm^2)

ACKNOWLEDGEMENT

Participation in conference was supported by grant of U.S. Department of Energy Ministry on topic “Advanced Wicks for Heat Pipes” in frame of partner project agreement P577 between Argonne National Laboratory, the Science and Technology Center in Ukraine and National Technical University of Ukraine "Kyiv Polytechnic Institute".

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