“DEVELOPMENT AND CREATION OF HEAT PIPES ON A BASIS METAL-FIBROUS CAPILLARY STRUCTURES WITH IMPROVED THERMOPHYSIC CHARACTERISTICS FOR TEMPERATURE CONTROL SYSTEMS OF THE PERSPECTIVE SPACE VEHICLES”

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INTRODUCTION

The researches on heat pipes (HP) are carried out at the I. Frantsevich Institute for Problems of Materials Science (IPMS) of National Academy of Sciences of Ukraine since 1970s. It is known that first HP has been designed in the USA (1966) in connection with development of space instrument-making. Complexity of heat sink, 90-95% of which have to be removed in order to ensure functioning of the space radio and electronic apparatuses, has caused the great interest to HPs of the engineers engaged in the area of thermal physics. The HPs exhibit super-high heat transfer characteristics thus enabling solving complex problems in heat removal. Due to application of HPs, it is possible either to eliminate systems of liquid cooling (with replacing it by air cooling) or use completely new non-traditional design approaches.

The designers of HPs know that the construction of a capillary structure (CS) of HP is of greatest importance in designing highly efficient HPs that are able to transmit (remove) the relatively large heat fluxes QHP with low values of thermal resistance RHP. The capillary structure has to meet two important functions of HP, namely: i) hydrodynamic (transfer of work liquid coolant under different orientation of HP in a gravitational field), and ii) thermal-physic (high intensity of heat exchange in heating and cooling zones of HP). As in numerous thermal-physic applications, the simultaneous realization of hydrodynamic and thermal-physic factors often gives an opposite effect, i.e. improvement “hydrodynamics” results in deterioration in “thermal-physics” of process.

It is known that the layers of metal grids have been used as a CS in the first designed HPs. The substantiation for this stemmed from availability of cellular materials because these are produced at a commercial scale. However, as was shown by experience gained in using cellular materials as CS in a HP, these exhibited improper thermal-physic and service characteristics. In particular, the unsatisfactory distribution of pores with respect to their sizes that is characteristic of cellular materials, results in failure in stability of evaporation and boiling processes in heating zones of HP, and also imposes substantial limitations on the values of heat fluxes transmitted by HP. Moreover, in manufacturing HP, the cellular materials are normally packed up in few layers thus resulting in the formation of local relatively large thermal resistance for heat removal, including contact thermal resistance.
As compared with cellular CS, the best results give metal powdered capillary structures (MPCS). In contrast to cellular CS, the MPCS has pore size distribution that ensures stable boiling in the heating zone. However, the MPCS has a number of disadvantages. To those relate in particular: i) presence of a large amount of closed (dead-end) pores; ii) low height of capillary raise of liquid; iii) decrease in permeability of CS due to increased hydraulic resistance caused by features in the construction of metal powdered structures. The first shortcoming results in the so called “thermal hysteresis” that arises with increase and decrease in the values of heat fluxes transmitted to HP. With hysteresis, the values of characteristic temperature drop \( \Delta T = T_{\text{wall}} - T_{\text{liquid}} \) are different, and this is undesirable in providing cooling elements with normal thermal stabilization conditions. The second and third shortcomings deteriorate service properties of HPs.

The technology for manufacturing metal fiber capillary structures (MFCS) has been developed, and the main physical characteristics of them have been studied at the IPMS under leadership of Academician A. G. Kostornov [1]. These MFCSs have virtually no the above mentioned shortcomings. Due to features in the construction, the MFCS has no dead-end pores thus eliminating the undesirable heat hysteresis. The MFCS provides HP with high hydrodynamic characteristics (good permeability, relatively high capillary rising of work liquid) and also with high thermal- physic characteristics (possibility for functioning HP under conditions of stable boiling of work liquid in heating zone, high intensity of heat exchange (due to boiling), and high ultimate values (with respect to heat removal) of critical heat fluxes). The MFCS has good physicomechanical and service characteristics. The technology for manufacturing MFCS gives stable and reproducible parameters, long service life, high reliability in functioning, and possibility for plastic deforming if it is required by construction. The latter feature of HP with MFCS is an important factor in practical use of HPs in real systems and constructions of modern apparatuses.

The main characteristics of HP and MFCS developed at the IPMS are the following:

1) the materials used in MFCS are copper, stainless steel, carbon steel, and nichrome;
2) the materials used in manufacturing case of HP are copper and stainless steel;
3) MFCS porosity — 10-97%;
4) MFCS thickness — 0.2-10 mm;
5) MFCS length — up to 4 m;
6) diameter of initial metal fibers — 20-80 μm;
7) fiber length — 2-10 mm;
8) average (effective) pore diameter — 10-250 μm;
9) maximum pore diameter — 20-500 μm.

The MFCSs are manufactured by the fiber metallurgy technology with process developed at IPMS. The main technological operations in manufacturing the HP with MFCS are the following:
1) manufacturing of cases and parts for HP;
2) preparation of monodisperse fibers by cutting bunches of metal wire;
3) gravitational deposition of fibers;
4) sintering of metal felt under specified time-temperature regimes;
5) rolling of felt plates to required thickness and porosity;
6) putting of MFCS blanks into HP cases;
7) joining of MFCS with HP case;
8) evacuation of manufactured HP blank;
9) injection of necessary amount of work liquid into HP blank;
10) sealing of HP;
11) serviceability tests with manufactured HPs.

The main directions of researches carried out at IPMS in the field of HP and capillary-porous structures are the following:
1) studying of the parameters of pore space in new types of CS produced on the basis of fiber and composite materials [2];
2) studying of the hydrodynamic characteristics of layered and gradient CS;
3) studying of the thermal-physic characteristics of CS of various types produced from fibers and composites based on them;
4) studying of the thermal-physic processes on metal surfaces with applied on them CS of new types.

The researches include: studying of the boiling process on the surfaces with porous coatings in dependence on their structure-hydrodynamic characteristics; investigation of
influence of those characteristics on contact thermal resistance between porous and solid layers; examination of heat exchange upon condensation of work liquids onto porous surfaces.

Recently, the works are carrying out at the IPMS aimed to investigation of influence of microgravity on the parameters and characteristics of HPs designed for application in systems of space technics. It is known that decrease in gravity level can affect the intensity of boiling process.

1.1 SELECTION OF UNIFORM AND LAYER-GRADIENT CAPILLARY STRUCTURES WITH OPTIMUM THIKNESS AND POROSITY (IPMS)

For more than 30 years, the researches are performed at IPMS aimed to designing highly efficient CSs and HPs based on them. The results of researches have been presented in 5 monographs, 80 scientific papers, and 60 patents.

Based on the results obtained, a series of efficient heat-transmitting devices of evaporation-condensation type have been designed. These are:

- devices for cooling thermally loaded units of space apparatuses;
- systems for cooling powerful clinotrons;
- precision thermostats based on coaxial HP;
- stands for electrical and thermal testing of powerful transistors;
- devices of medical purposes for local freezing, etc.

The comprehensive tests of designed heat-transmitting devices have been carried out under conditions of sever mechanical and heat effects (vibrations, shocks, linear accelerations, thermal ageing, thermal cycling), and also long-term and short-term tests of HPs. It was revealed that the HPs designed can operate with any orientation in the space, they allow for bending with complicated profile without deterioration of thermal-physic parameters.

In traditional porous materials (powdered, fibrous, cellular), there is strong dependence of virtually all the properties on porosity. This dependence can be eliminated by combining in one material of the structural elements with different geometrical dimensions, and therefore different packing density.

In current project, new layered materials containing both linear (fibers) and point (powder) structural elements will be used in designing CS.
Different densification mechanisms are realized in such materials, namely: merely contact character of powder densification under easier moving of particles via mutual sliding, and flexibly-rigid character of fiber densification when not only contact deformation but also reversible elastic and irreversible plastic deformations take place. So, depending on the ratio of dimensions of powder and fiber particles, of thicknesses of fiber and powder layers the range in variation of the structural characteristics of these materials is considerably widened.

The process has been studied for gravitational forming of highly porous composite materials from metal powders and fibers. The sheet-shaped samples of materials were manufactured through layer-by-layer deposition of stainless steel fibers (diameter 30-100 μm) and powders (particle size 0.04-0.3 mm) with application of vibrations.

The investigations have shown that depending on the ratio of dimensions of powder particles (dp) and fibers (df), and also of thicknesses of fiber and powder layers, the different types of material macrostructure are formed. The structures with distinct fiber and powder layers are formed with ratio $dp/df > 2$ (Fig.1.1.1). With $dp/df < 2$, the powder partly or completely deposits in a preliminary formed highly porous fiber carcass. Such composites are the most prospective from the viewpoint of using them as CS in HP (Fig. 1.1.2).

![Layered porous fiber-powder composite.](image)
Fig. 1.1.2 — SEM image of porous carcass-type fiber-powder composite.

Three types of layered CS have been prepared:

- merely fiber CS consisting of one 0.75 mm thickness layer of fibers 50 μm in diameter and one 0.25 mm thickness layer of fibers 30 μm in diameter;
- fiber-powder CS as a carcass of 1 mm thickness made of fibers 50 μm in diameter and filled from one side at a depth 0.25 mm with powder of 60 μm particle size;
- fiber-powder CS as a carcass of 1 mm thickness made of fibers of 30 μm in diameter and filled from one side at a depth 0.25 mm with powder of 40 μm particle size.

Table 1 lists the characteristics of pilot CSs.
Table 1

<table>
<thead>
<tr>
<th>Specim. №</th>
<th>Mass, g</th>
<th>Thickness, mm</th>
<th>Width, mm</th>
<th>Length, mm</th>
<th>Average porosity, %</th>
<th>Material composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>35</td>
<td>1,0</td>
<td>50</td>
<td>300</td>
<td>70,2</td>
<td>One 0.75 mm thickness layer of fibers 50 μm in diameter and one 0.25 mm thickness layer of fibers 30 μm in diameter</td>
</tr>
<tr>
<td>2</td>
<td>24</td>
<td>1,0</td>
<td>50</td>
<td>300</td>
<td>80,4</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>1,0</td>
<td>50</td>
<td>300</td>
<td>91,5</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>36</td>
<td>1,0</td>
<td>50</td>
<td>300</td>
<td>69,3</td>
<td>Layer of 1 mm thickness of fibers</td>
</tr>
<tr>
<td>5</td>
<td>28</td>
<td>1,0</td>
<td>50</td>
<td>300</td>
<td>76,2</td>
<td></td>
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<tr>
<td>6</td>
<td>20</td>
<td>1,0</td>
<td>50</td>
<td>300</td>
<td>82,0</td>
<td>Layer of 1 mm thickness of fibers 50 μm in diameter filled from one side at a depth 0.25 mm with powder of 60 μm particle size</td>
</tr>
<tr>
<td>7</td>
<td>34</td>
<td>1,1</td>
<td>50</td>
<td>300</td>
<td>70,0</td>
<td></td>
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<tr>
<td>8</td>
<td>28</td>
<td>1,0</td>
<td>50</td>
<td>300</td>
<td>76,0</td>
<td>Layer of 1 mm thickness of fibers 50 μm in diameter filled from one side at a depth 0.25 mm with powder of 40 μm particle size</td>
</tr>
<tr>
<td>9</td>
<td>20</td>
<td>1,0</td>
<td>50</td>
<td>300</td>
<td>82,0</td>
<td></td>
</tr>
</tbody>
</table>
1.2 THEORETICAL MODEL FOR HEAT EXCHANGE IN PHASE TRANSFORMATIONS OF LIQUIDS ON THE SURFACES WITH CAPILLARY-POREOUS STRUCTURES (GERI)

Reasoning from physical ideas and approaches in understanding the boiling process, we have suggested the following approximate physical model for heat exchange upon boiling on the surfaces covered with capillary-porous structures (CS). The model is based on the following assumptions.

1. The real pore structure (Fig. 1.2.1, a) is replaced with idealized one consisting of the series of pores of regular geometrical shape, which steadily function and generate vapor (“vapor” pores), and of pore space filled completely with liquid (“liquid” pores) (Fig. 1.2.1, b).

2. The diameter of “vapor” pores varies from \( D_{\text{max}} \) at the start of liquid boiling (Fig. 1.2.2, a) to \( D_{\text{min}} \). In this case, the ratio \( \varepsilon \) of total cross section area of pores which generate vapor, \( F_v \), to heating surface area \( F \) varies from 0 to \( \varepsilon_{\text{max}} \) (Fig. 1.2.2, c).

3. The heat is transferred from the heating surface by three ways, namely: due to effective heat conductivity of CS and convection of liquid (\( q'_1 \)); due to creation of micro-ribs on the heating surface, i.e. via micro-film of liquid on the walls of “vapor” pores (\( q'_1' \)); due to evaporation of micro-layer of liquid at the basis of “vapor” pores (\( q'_2 \)) (Fig. 1.2.3, b).

4. The heat conductivity of the capillary-pore structure and of the liquid in CS area which is not occupied by “vapor” pores is replaced by integral heat conductivity \( \lambda_{\text{eff}} \).

5. The micro-film of liquid exists on the walls of “vapor” pores, the thickness of which, \( \delta_{lf} \), is constant over the pore wall.

6. The micro-layer of liquid exists at the basis of “vapor” pores, whose thickness, \( \delta_{ll} \), is constant over the pore cross section.

In accordance with proposed approximate model, there is total (alternating in accordance with physical characteristics of CS) thermal resistance for heat removal, \( R_{\text{CS}} \), in boiling of liquid on the surface covered with CS. That resistance is a sum of three thermal resistances \( R'_1', R''_1', R_2 \) that correspond to the considered above heat flux densities.
The total density of heat flux in boiling of liquid on the surface covered with CS under conditions of free liquid movement can be calculated by the formula

\[ q = q_1' + q_1'' + q_2 = \frac{\Delta T}{R_1'} \cdot (1 - \varepsilon) + \frac{\Delta T - \Delta T^*}{R_1''} \cdot (1 - \varepsilon) + \frac{\Delta T - \Delta T^*}{R_2} \cdot \varepsilon \]  \hspace{1cm} (1)

Here \( \Delta T \) is temperature difference between the wall (heating surface) and liquid, \( \Delta T^* \) is temperature drop for the start of liquid boiling, and the thermal resistance for heat removal \( R_1' \) (due to convection and effective heat conductivity of pore area of CS occupied by liquid) can be determined from the formula:

\[ R_1' = R_{cont} \cdot \frac{\delta_{CS}}{\lambda_{eff}} + \frac{\delta_{bl} - \delta_{CS}}{\lambda_t}, \]

where \( R_{cont} \) is thermal resistance of the contact of heating surface of CS; \( \delta_{bl} \) is thickness of boundary layer; \( \delta_{CS} \) is thickness of CS. The \( R_{cont} \) depends on the quality of joint of CS with surface.

The thickness of boundary layer \( \delta_{bl} \) for surface with CS (in assumption that it is the same that for smooth surface) can be determined via known dependencies used for calculation of heat exchange under conditions of free convection of liquid.

Fig 1.2.1 — Schematic drawing of processes for vapor formation and heat exchange on the surface covered with CS under conditions of free movement of liquid: a) real conditions for contact heat exchange; b) idealized conditions of approximate physical model.
Fig. 1.2.2 — Variation in the surface area of vapor generating pores in CS in relation to the density of heat flux: a) low values of $q$; b) elevated values of $q$; c) ultimate values of $q$. Shaded are pores filled with single-phase liquid, and un-shaded are pores filled with vapor.

Fig. 1.2.3 — Schematic drawing of heat exchange upon boiling on smooth technical surface (a) and on surface covered with porous structure (b): $q_1$ is portion of total density of heat flux removed from heating surface by liquid phase; $q_2$ is portion of total density of heat flux removed from heating surface by vapor phase; $q'_1$ is portion of density of heat flux $q_1$, which is removed from the heating surface by liquid phase but not transferred to the vapor phase; $q''_1$ is portion of density of heat flux $q_1$, which is removed from the heating surface by liquid phase and transferred to the vapor phase (i. e. to vapor bubble.
which did not lose touch with heating surface); $q_i''$ is portion of density of heat flux $q_i$, which is removed from the heating surface by liquid phase and transferred to the vapor phase (i.e., to vapor bubble which lost touch with heating surface); $\lambda_i$ is heat conductivity coefficient for liquid; $\lambda_{eff}$ is heat conductivity coefficient for CS saturated with liquid; $\lambda_{ll}$ is heat conductivity coefficient for liquid micro-layer at the basis (bottom) of vapor pore; $\delta_{ll}$ is thickness of liquid micro-layer at the basis (bottom) of vapor pore; $\delta_{lf}$ is thickness of liquid micro-film at the side wall of vapor pore.

Fig. 1.2.4 — Diagram for heat exchange in a single “vapor” pore: a) part of single pore corresponding to the model; b) distribution of temperature over pore height: $\alpha_1$ is heat-transfer coefficient at the side wall of vapor pore; $\alpha_2$ is heat-transfer coefficient at the basis (bottom) of vapor pore; $\theta_0$ is temperature difference between heating surface and boiling liquid; $\theta_1$ is temperature difference between the side wall of vapor pore and boiling liquid; $\Delta T$ is temperature difference between the wall (heating surface) and liquid; $\Delta T^*$ is temperature drop for the start of liquid boiling; $l$ is height (Y coordinate); $\Delta T_0$ is calculated value for $\Delta T$.

The calculation of the values of $R_i'$ within the limits for variation of characteristics of CS has made it possible to determine that $3.4 \cdot 10^{-5} < R_i' \leq 3.7 \cdot 10^{-3}$ (m$^2$-K)/W. To determine the value of $R_i''$, it is necessary to account for the scheme for heat exchange in single “vapor” pore (Fig. 1.2.3, a). When solving the task which is similar to known that for heat conductivity in a rod, we use some features in limiting conditions which can be considered as correct:
\[ \frac{d^2 \vartheta}{dx^2} - m^2 \vartheta = 0 \]
\[ m^2 = \frac{\alpha}{\lambda_{ef}} \cdot \frac{U}{f} \]

where \( \vartheta \) is average temperature difference for pore skeleton; \( x = 0, \ \vartheta_0 = \Delta T_0 - \Delta T^*; \)
\( x = l, \ \vartheta = 0; \ x = \delta_{cs}, \vartheta = -\Delta T^*. \)

Using the solution obtained, one can find the amount of heat that is removed by the walls of single “vapor” pore:

\[ \frac{Q}{f} = \lambda_{ef} \cdot m \cdot \vartheta \cdot 2ch \cdot \frac{ml}{\exp(ml) - 1}, \]  \hspace{1cm} (2)

where \((m \cdot l)\) is determined from expression

\[ \Delta T^* \cdot [\exp(ml) - 1] = 2(\Delta T - \Delta T^*) \cdot sh[m(\delta_{cs} - l)] \].  \hspace{1cm} (3)

The ratio of perimeter \( U \) of conventional cylindrical edge (rod-shaped) to its surface area \( f \) can be approximately found from relationships:

\[ U = \pi D; \ f = \pi \cdot D^2 / 4 = 1 - \varepsilon; \ D = \sqrt{4 \cdot (1 - \varepsilon) / \pi}; \ U / f = 4 / D = [4 \pi / (1 - \varepsilon)]^{0.5} \]  \hspace{1cm} (4)

The value of \( m \) with adopted scheme for heat exchange can be calculated by formula

\[ m = \sqrt{\frac{\lambda_i}{\lambda_{ef}} \cdot \frac{1}{f}} \cdot \sqrt{\frac{\lambda_i}{\lambda_{ef}} \cdot \frac{4 \pi}{1 - \varepsilon}^{1/2}}. \]  \hspace{1cm} (5)

To calculate the thickness of liquid micro-film that covers walls of vapor-generating pore, we use the formula

\[ \delta_y = 0.42 D \cdot \left( \frac{\mu_i \cdot W_v}{\sigma_l} \right)^{0.2}, \]  \hspace{1cm} (6)

where \( W_v \) is vapor velocity in a “vapor” pore (pore channel), \( D \) is pore (channel) diameter, \( \mu_i \) is dynamic coefficient of liquid viscosity, \( \sigma_l \) is surface tension coefficient for liquid. \( W_v \) can be determined by formula:

\[ W_v = 2 q_p \cdot \delta_{cs} / r_v \cdot \rho_v \cdot D \cdot \phi, \]  \hspace{1cm} (7)

where \( q_p \) is average density of heat flux over pore height, \( r_v \) is specific heat for vapor formation, \( \rho_v \) is vapor density, and \( \phi \) is coefficient which accounts for the time for moving of vapor and
liquid phases over the pore. The calculations showed that the value of $m$ varies in the range 50-1000.

The value of $R''_1$ calculated with above formulae and dependencies varies within the limits: $2 \cdot 10^{-4} \frac{m^2 \cdot K}{W} \leq R''_1 \leq 1 \cdot 10^{-3} \frac{m^2 \cdot K}{W}$. As seen from the techniques for calculation $R''_1$, the value of that quantity depends substantially on geometric, structural, and thermalphysic characteristics of CS, on conditions for contact of CS with carrying solid surface, and also on the value of temperature drop.

The value of $R_2$ can be calculated in the first approximation, if the thickness of micro-layer in the base of a “vapor” pore is known. The calculations showed that $\delta_{ll}$ is 10- to-15 $\mu$m. From some other estimates, the thickness of micro-layer can be in the range 5-50 $\mu$m. For this range, $R_2 = (7-70) \cdot 10^{-6}$ (m$^2$-K)/W. Assuming that range to be initial and neglecting the surface area of possible dry spot in the center of “vapor’ pore we suggest that $R_2 = (7-70) \cdot 10^{-6}$ (m$^2$-K)/W.

Thus, if one assumes that the thickness of liquid micro-layer under bubble $\delta_{ll}$ decreases little with increase in the density of heat flux, then $R_2$ can also vary, and that variation is considerably less compared to the second component ($R_1$).

When calculated the values of $R'_1$, $R''_1$, and $R_2$ with specified set of characteristics of CS and the density of heat flux, one can determine the value of temperature drop $\Delta T$. To calculate $\Delta T$, it is also necessary to determine the value of $\varepsilon$, i.e. ratio of the surface area of bases of “vapor” pores to the surface area of heating surface $F$. In general case, $\varepsilon$ depends on geometric, thermalphysic, and structural characteristics of CS, including pore size distribution. The results of calculations show that influence on $\varepsilon$ of either characteristic that determines parameters of CS is different. In the end, the value of $\varepsilon$ depends on the set of physical characteristics of CS, and it can be presented as empirical dependence

$$\varepsilon = k \cdot q^{n_1} \cdot \delta_{cs}^{n_2} \cdot \lambda_k^{n_3} \cdot \Pi^{n_4} \cdot D_{eff}^{n_5},$$

where $\lambda_k$ is heat conductivity of carcass (CS) without liquid, $\Pi$ is porosity, and the exponents $n1$-$n5$ and constant $k$ can be determined by experiment. The nature of variation of $\varepsilon$ is conservative, and this fact facilitates practical use of relationship (8).
The results of calculating thermal resistances $R_1$, $R_1''$, and $R_2$ indicate that these quantities are commensurable. Thus, it can be suggested that variation of physical characteristics of CS over wide range and the contact conditions for CS with heat-loaded solid bearing surfaces can substantially affect the character and intensity of heat exchange upon boiling on porous surfaces.

2.1 MANUFACTURING AND EXAMINATION STRUCTURE-HYDRODYNAMIC CHARACTERISTICS OF MODEL CAPILLARY STRUCTURES (IPMS)

The series of investigations has been carried out on INTAS project №06-1000024-9339 concerning hydrodynamic, structural, physic mechanical, and capillary-transport characteristics of porous materials made from fibers and powders of stainless steel, which are promising for using them as capillary structures (CS). The objects for investigations were layered fibrous materials that contained layers of fibres of 30 and 50 μm in diameter, carcass-type fibres-powder composites as carcass made from fibres 30 or 50 μm in diameter partially filled with powder with particles of 40 or 80 μm in size. The macro-structures of layers in fibres-powder composites are shown in Fig. 2.1.1.

The production process for making pilot samples of materials can be conventionally divided into two stages. In the first stage, the sheet-shaped billets of (1-3)×100×350 mm size were prepared by uniform layer-wise vibrating deposition of fibres and powders, which then were sintered and rolled. In the second stage, the specimens with specified structure characteristics have been manufactured from those billets in the form of rods 20 mm in diameter for structural study, plates of (1-3)×6×80 mm in size for examination physic mechanical properties, and plates of (1-2)×20×300 mm in size for investigation the kinetics of capillary suction.

Analysis of processes that occur in heat pipes (HP) shows that ideal permeable material for making CS has to satisfy a number of requirements which are often contradictory, namely:

1. The material must allow realization and change in a wide range of structural, hydrodynamic, and physic mechanical characteristics.
2. The material must allow manufacturing thin sheet-shaped billets of large size with uniform porous structure.

3. The porous carcass must exhibit maximum heat conductivity.

4. The properties of material have to be reproducible and predictable quantitatively.

The main characteristics of any porous material which is supposed to be used as CS (as it follows from equation for pressure balance in [3]) are the coefficient of permeability and average pore size which influence the velocity of heat carrier flow.

The average pore diameter in specimens was calculated based on two experimentally determined characteristics of the material, namely open porosity and air permeability. The calculation was based on assumption of the fact that all the porous channels are of the same cross section and of cylinder shape, these are displaced parallel each other and to material surface. The pilot samples of 20 mm in diameter, 1 mm thick, and porosity 70-90% were clamped in special casing and blown through with air. The pressure difference within the specimens was measured by differential manometer, while air consumption by flow-meter. The dependences obtained for air consumption vs. pressure difference were treated by the formula in [4] in order to calculate average pore diameter (in μm):

$$D_{\text{ave}} = 55.56 \sqrt{\frac{K}{Q}}$$

where $K$ is coefficient of gas permeability, $\times 10^{-12}$, $m^2$, and $Q$ is porosity, %.

The results of study structure-hydrodynamic characteristics of high-porous samples made of fibers and powders of stainless steel are listed in Table 1.1. It was revealed that fiber-powder composites have higher pore size than one-layer and two-layer pure fibrous materials.
Fig. 2.1.1 — Macro-structure of fiber-powder composites: a – layer of fibers 30 μm in diameter; b – layer of powder with 80 μm particle size.

As seen from Fig. 2.1.2, the samples with layer of fibers 50 μm in diameter and powder layer with particles size 80 μm and porosity 80% contain pores with sizes less by a factor of 2.2 and 1.2 compared with one-layer samples of fibers 50 μm in diameter and two-layer samples of fibers 30 and 50 μm in diameter, respectively. Upon decreasing porosity and increasing dispersity of fibers and powders, the pore sizes in pure fiber samples decrease also but they do not reach values peculiar to fiber-powder composites.

The observed differences in pore sizes in studied porous materials are due to first of all different packing density of metal fibers and powders in the absence of load, and densification under effect of load [5]. Therefore, the range of pore size change over the sample thickness increases.

For instance, in material of 64% porosity that contains layer of fibers 30 μm in diameter with maximum and average pore sizes 100 μm and 45 μm, respectively, and powder layer with particle size 40 μm and maximum and average pore sizes 9 μm and 2 μm, respectively, the gradient of maximum pore sizes over material thickness is 10 while that for average pore sizes is 22 (Fig. 2.1.3).
Table 1.1

The results of study structure-hydrodynamic characteristics of samples made from stainless steel fibers and powders

<table>
<thead>
<tr>
<th>№</th>
<th>Thickness, mm</th>
<th>Porosity, %</th>
<th>Permeability coefficient, $10^{-12}$ m$^2$</th>
<th>Average hydraulic pore size, μm</th>
<th>Composition of samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>70</td>
<td>46</td>
<td></td>
<td>Layer of fibers of 50 μm in diameter</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>80</td>
<td>58</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>90</td>
<td>85</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>70</td>
<td>40</td>
<td></td>
<td>Layer of fibers of 30 μm in diameter</td>
</tr>
<tr>
<td>5</td>
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<td>80</td>
<td>52</td>
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<td></td>
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<tr>
<td>6</td>
<td>1</td>
<td>90</td>
<td>75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>66</td>
<td>20</td>
<td>30</td>
<td>Two-layer composite: one layer of fibers of 50 μm in diameter, and one layer of fibers of 30 μm in diameter</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>78</td>
<td>25</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>89</td>
<td>32</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>70,3</td>
<td>17</td>
<td>25</td>
<td>Composite as carcass made of fibers of 50 μm in diameter partially filled with powder with particle size 80 μm</td>
</tr>
<tr>
<td>11</td>
<td>1</td>
<td>81,4</td>
<td>21</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>1</td>
<td>86</td>
<td>26</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>1</td>
<td>70,5</td>
<td>12</td>
<td>20</td>
<td>Composite as carcass made of fibers of 30 μm in diameter partially filled with powder with particle size 40 μm</td>
</tr>
<tr>
<td>14</td>
<td>1</td>
<td>80,4</td>
<td>17</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>1</td>
<td>86</td>
<td>22</td>
<td>26</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2.1.2 — Dependence of average pore size on porosity for one-layer and two-layer materials made of stainless steel fibers and powders; 1 – layer of fibers of 50 μm in diameter, 2 - layer of fibers of 30 μm in diameter, 3 - composite as a layer of fibers of 50 μm in diameter and layer of fibers of 30 μm in diameter, 4 - composite as a carcass of fibers of 50 μm in diameter
partially filled with powders with particle size 80 μm, 5 - composite as a carcass of fibers of 30 μm in diameter partially filled with powders with particle size 40 μm.

![Graph showing pore distribution](image)

Fig. 2.1.3 — Differential and integral curves for pore distribution within material containing 1.5 mm thick layer of fibers 30 μm in diameter and 0.5 mm thick powder layer with particle size 40 μm

Among the physicomechanical properties of the materials developed, the electrical conductivity and mechanical strength are of greatest importance.

The electrical resistance of pilot samples of materials was measured with special unit at room temperature. The elasticity modulus was measured by static method in four-point bending mode [6] with test unit equipped with high-sensitive gage with an error ±5%.

The results obtained showed that the dependences of resistance and elasticity modulus on porosity are of similar nature. Pure fiber materials are superior with respect to resistance and elasticity of layered composites over the whole range of porosity variation, while the carcass-type materials exhibit better properties only at high porosity (>60%) (Fig. 2.1.4).

The differences in conductivity and elasticity of materials studied can be explained based on the concept of densification mechanisms of metal fibers and powders. It is known that compared with pure contact nature of densification powders upon easy displacement of
particles by mutual slipping, when compacting fibers not only the contact plastic deformation and also reversible and irreversible bend plastic deformation occurs. In this case, the originally straight fibers gain spiral shape and form numerous contacts when contacting with other fibers [5]. This probably causes high electrical conductivity of fibrous materials.

![Graph](image)

**Fig. 2.1.4 — Dependence of elastic modulus on porosity for porous one-layer and two-layer samples made of stainless steel fibers and powders: 1 – materials made of fibers 40 μm in diameter; 2 - layered composites (fibers of 40 μm in diameter and powder with particle size 160 μm); 3 – carcass-type composites (fibers of 40 μm in diameter and powder with particle size 40 μm)**

In layered fiber-powder composites, the contribution from the mechanism that governs flexible-rigid densification into the process of contact formation decreases. This first of all causes low conductivity of materials.

The two above densification mechanisms occur in carcass-type composites, but the conditions for occurring them in such materials are worse. In carcass-type materials, the pores are partially or completely filled with powders, so the fiber bending is hindered.

The process for introducing powder into fibrous carcass is accompanied by formation of new fiber-powder contacts thus causing ambiguous dependence of conductivity and elasticity of such materials on porosity. In case of high porosity, when probability for formation good inter-particle contacts is low, the carcass-type materials are
similar to pure fibrous materials with respect to conductivity and elasticity. In case of low porosity, with formation of high-quality contacts the carcass-type composites are superior of pure fibrous materials with respect to conductivity and elasticity.

The limitation in heat-transfer capacity due to transport properties of CS is one of the most important features in performance of HP. The transport properties of CS, which are determined by permeability, the average size, and the pore distribution within the material are evaluated via flow rate and ultimate rising height for heat carrier. The wetting angle also affects flow rate and rising height of heat carrier, but it depends only on surface phenomena that occur at interface “CS material-heat carrier”.

The kinetics of capillary transport was studied with special unit. The sample was placed vertically by guide rod in a work chamber. The strips of dry hygroscopic material were clamped to the surface of porous sample with clips connected consecutively to multi-channel level indicator and digital voltmeter. The chamber was equipped with lighting thus enabling visual monitoring of work liquid front under the pressure action, which develops by saturated vapour of liquid. The unit was filled with liquid up to specified level through measuring burette. To contact with liquid, the sample was dipped down by silphon. When the liquid rises under effect of capillary forces and contacts sensors, the electrical circuit bridges and this is indicated by level indicator and digital voltmeter.

The high-porous one-layer and two-layer pure fiber and carcass-type fiber-powder samples made of stainless steel as strips (1-2)×20×300 mm size have been studied. The ethanol was as a work liquid. The capillary transportation of ethanol was examined under the pressure of saturated vapour in a chamber up to complete impregnation of sample. Depending on the parameters of porous structure of material, the impregnation time was 3 to 10 hours. Some results of experimental study of the kinetics of capillary suction of ethanol by developed porous materials are presented in Fig. 2.1.5.
Fig. 2.1.5 — Height of ethanol capillary rise in materials made of stainless steel fiber and powders vs. time: 1 – composite made of fibers 50 μm in diameter and powder with particle size 80 μm (porosity 81.4%); 2 – composite made of fibers 50 μm in diameter and powder with particle size 80 μm (porosity 67.5%); 3 – composite made of fibers 30 μm in diameter and powder with particle size 40 μm (porosity 65.0%); 4 – composite made of fibers 50 μm in diameter and powder with particle size 80 μm (porosity 85.6%); 5 – composite made of fibers 50 μm in diameter and fibers 80 μm in diameter (porosity 85.0%); 6 – layer of fibers 30 μm in diameter (porosity 82.0%)

As seen from Fig. 2.1.5, the porous fiber-powder composites are characterized by satisfactory high capillary-transport capacity and essentially exceed porous one-layer and two-layer purely fibrous materials with respect to the rate and height of ethanol rising against gravity. The highest efficiency in capillary transport exhibited composites consisting of fibers 50 μm in diameter and powder with particle size 80 μm and porosity 67.5%. These exhibited also better combination of permeability characteristics and pore size, and are superior of one-layer and two-layer pure fibrous samples with respect to rising height of ethanol for 50 min by a factor of 2 and 1.8, respectively.

The investigation carried out make it possible to conclude that porous fiber-powder composites are very promising for use as capillary structures in heat pipes.
2.2 THERMO-PHYSICAL STUDIES OF MODEL CAPILLARY STRUCTURES
(GERI)

The calculation of thermo-physical characteristics of HP, in particular maximum heat transferring power $Q_{hp}$ and heat resistance $R_{hp}$ are based on the fact that the values of heat transfer coefficient $\alpha$, i.e. quantitative characteristics of heat transfer intensity in heat supply and heat removal zones of HP should be known. Non-isothermicity of those permits calculation of only mean values of $\alpha$ (over zone length). Because of difficulty in exact calculation of $\alpha$ values and determination of them immediately in HP, these are determined by experiment under conditions that simulate performance of HP. The units for study heat transfer upon evaporation and boiling on the surfaces of HP with CS have been designed at IPMS. These units allow experimental determination of real values $\alpha$ for various types of porous structures under conditions of both CS filled with liquid and when there is capillary inflow of the heat carrying liquid.

The construction of experimental unit for aforementioned investigations is schematically shown in Fig. 2.2.1.
Fig. 2.2.1 — Schematic drawing of unit for thermo-physical study of heat transfer upon boiling on the surfaces with capillary structure under conditions typical for HP performance: 1 – copper wedge; 2 – main heater; 3 – guard heater; 4 – sample of CS; 5 – flange; 6 – cylinder; 7 – cover; 8 – connections; 9 – thermocouples; 10 – cylinder; 11 – casing; 12 – system with guard heater; 13 – system for voltage stabilization and power measuring; 14 – vacuum pump; 15 – receiver; 16 – measuring instruments; 17 – condenser; 18 – tank; 19 – vessel; 20 – temperature measuring system.

In Fig. 2.2.2, the schemes are shown for work parts of experimental unit, which are destined for investigation of conditions typical for HP performance.
Fig. 2.2.2 — Construction of work parts destined for thermo-physical study of boiling process on the surfaces of HP with CS for conditions: A – filling with liquid, B – capillary inflow of liquid; 1 – copper heat supplier; 2 – electric heater; 3 – cylinder; 4 – thermocouple; 5 – guard heater; 6 – protective casing; 7 – teflon flange; 8 – thermocouples; 9 – test sample of CS; 10 – glass cup; 11 – heat insulator; 12 – flange; 13 – thermocouples; 14 – connections; 15 – porous structure; 16 – stop; 17 – flange; 18 – copper wedge.
The curves plotted from experimental data are:
I – maximum values of $\alpha$ on surfaces with metal-fiber CS;
II – minimum values of $\alpha$ on surfaces with metal-fiber CS;
III – values of $\alpha$ on smooth technical surfaces (published data).
The points determined from experiment are:
1 – CS porosity $\theta = 40\%$; CS thickness 0.6 mm;
2 – CS porosity $\theta = 87\%$; CS thickness 0.6 mm;
3 – smooth technical surface.
An arrow indicates critical boiling regime.

Fig. 2.2.3 — Intensity of heat transfer upon water boiling on the surfaces with copper metal-fiber CS under conditions of filling with liquid (work part A of the unit).

Some results obtained during study of water boiling intensity on the surfaces with copper fibrous CS (under atmospheric pressure) are presented in Fig. 2.2.3 as the dependence of change in heat transfer coefficient $\alpha$ [W/m²·K] on the density of heat flux $q$ [W/m²].

Analysis of the results in Fig. 2.2.3 makes it possible to conclude that moderate-porous metal-fiber structures (points 1) provide with high values of heat transfer coefficient $\alpha$ (by a factor of 5-10 higher than the values typical for boiling on smooth technical surfaces). High-porous metal-fiber CS (points 2) gives $\alpha$ values less than those typical for moderate-porous metal-fiber CS. At the same time, high-porous metal-fiber CS gives very high values of critical density for heat flux $q_{cri}$ (at which the boiling crisis occurs), which are higher by a factor of 3-4 than values typical for smooth technical surfaces.

The results obtained substantiated the idea for creating “hybrid” or so called “gradient” metal-fiber capillary structures in which positive thermo-physical properties of moderate-porous and high-porous CSs are combined. These structures have been designed as the alternating (with respect to the heat transfer surface area) parts of metal-fiber CS with moderate and high porosity (Fig. 2.2.4).
Fig. 2.2.4 — Samples of “gradient” metal-fiber capillary structures with alternating (with respect to heat transfer surface area) porosity.

A set of experimental results obtained under conditions of water boiling on the surfaces with gradient metal-fiber capillary structures is shown in Fig. 2.2.5. The ratio of surface areas for moderate-porous and high-porous capillary structures ($\theta_{mcs}/(\theta_{hcs})$) varied in the range 0.5-0.85. The values of heat density flux $q$ varied in the range (0-250)$\cdot10^4$ W/m².

Analysis of experimental data confirms the expediency of creating “hybrid” (or “gradient”) capillary structures. It is known that high-porous CS provide HP with high heat transfer characteristics. The moderate-porous CS, apart from high intensity of heat transfer, give high values of capillary rise for liquid. These CS are preferentially usable in HPs which work under conditions of counter-effect of gravity. With a set of reliable experimental data, i.e. the values of heat transfer coefficient for different ranges of variation of capillary structures characteristics and liquids-carriers of heat, it becomes possible to intentionally control the HP characteristics during designing heat pipes on account of specific conditions for functioning of heat pipes of special purposes.
1 – smooth copper surface; 2 – surface with high-porous metal-fiber structure ($\theta_{hcs} = 87\%$, thickness of CS $\delta_{cs} = 1.0$ mm); 3 – surface with gradient metal-fiber structure ($\theta_{mcs}/(\theta_{hcs} = 0.5$, $\delta_{cs} = 1.0$ mm); 4 - surface with gradient metal-fiber structure ($\theta_{mcs}/(\theta_{hcs} = 0.7$, $\delta_{cs} = 1.0$ mm); 5 - surface with gradient metal-fiber structure ($\theta_{mcs}/(\theta_{hcs} = 0.85$, $\delta_{cs} = 1.0$ mm); 6 – surface with moderate-porous metal-fiber structure ($\theta_{mcs} = 50\%$, $\delta_{cs} = 1.0$ mm). Arrows indicate crisis boiling.

Fig. 2.2.5 — Intensity of heat transfer upon water boiling under conditions of filling with liquid on the surfaces with usual and gradient metal-fiber structures. Experimental points correspond to.
3.1 EXAMINATION OF HYDRODYNAMIC CHARACTERISTICS OF CAPILLARY-POREOUS MATERIALS (IPMS, GERI)

To calculate characteristics of heat pipes in which capillary-porous materials are used it is necessary to know hydrodynamic (or capillary-transport) characteristics of capillary-porous materials. To those characteristics relate first of all the height of capillary rise of liquid and the velocity of transportation of liquid heat carrier in the porous structure, and these are examined as a rule by experiment.

The experimental examination of hydrodynamic processes in capillary-porous materials (structures) and transport characteristics have been performed with pilot unit designed and constructed at the IPMS (Fig. 3.1.1, 3.1.2). It is known that in the absence of pressure gradient the liquid in porous body is transported under effect of capillary head which is determined by the formula

\[ \Delta P = 4 \cdot \sigma \cdot \cos \alpha / D_{\text{eff}}, \] (3.1.1)

where \( \sigma \) is surface tension of liquid, \( \alpha \) is wetting angle, \( D_{\text{eff}} \) is average effective pore size in the material. The capillary head is balanced by losses in liquid pressure due to friction in material, which for laminar flow are

\[ \Delta P_L = 32 \cdot V \cdot \mu \cdot L \cdot B^2 / D_{\text{eff}}^2, \] (3.1.2)

where \( V \) is average velocity of liquid flow having viscosity \( \mu \), \( L \) is distance for which liquid front displaces in material, and \( B \) is sinuosity coefficient of porous channels.

Generally, with random spatial orientation of material samples the capillary head is balanced by pressure difference in the liquid caused by gravitational forces

\[ \Delta P_g = \rho \cdot g \cdot L \cdot \sin \varphi, \] (3.1.3)

where \( \rho \) is liquid density, \( g \) is gravity, and \( \varphi \) is angle of sample tilt.

The maximum velocity of capillary suction is

\[ V_{\max} = D_{\text{eff}}^2 \cdot \sigma \cdot \cos \alpha / 8 \cdot \mu \cdot L \cdot B^2, \] (3.1.4)

while the maximum height of capillary rising of liquid is

\[ H_{\max} = 4 \cdot \sigma \cdot \cos \alpha / D_{\text{eff}} \cdot \rho \cdot g. \] (3.1.5)
The model relationship between impregnation kinetics, parameters of porous body structure, and physical properties of liquid allows quantitative evaluation of flow movement in material pores, as well as of adhesion work at solid-liquid interface. The necessary data on the characteristics of porous space are determined preliminary with samples of capillary structures with regular porous structure. The average hydraulic diameters of pore channels are determined, in particular, by the method of forcing out liquid from pores by gas, while the sinuosity coefficient is calculated from the ratio of equilibrium average hydraulic pore diameter to its value determined by the method of gas permeability. The kinetics of capillary transport is examined with experimental units similar to that shown in Figs. 3.1.1 and 3.1.2. The sample of capillary-porous structure (CS) is placed vertically by pilot pin in a work chamber. The strips of 3 mm width made of dry hygroscopic material are pressed to the surface of porous sample by clamps connected sequentially to multi-channel level indicator (12) and digital voltmeter. The work chamber equipped with light allows visual monitoring of the displacement of work liquid front both at pressure of its saturation vapor and in vacuum (10 \( -10^3 \) Pa). The unit is filled with liquid up to work level through the burette. To contact with liquid, the sample is moved down by boot. When liquid is capillary suctioned by CS sample, the electric circle is closed-in sequentially to clamps, and the closing-in is detected by level indicator and digital voltmeter through the change in current value. When examining, the curve for variation in the height of capillary rise \( H \) vs. time \( \tau \) is recorded until equilibrium value \( H_{\text{max}} \) is reached. From those curves by graphic differentiation the variation in suction rate with time is determined: \( \frac{dH}{d\tau} = f(\tau) \). When the dimensions of porous material sample in the direction of capillary transport is less than \( H_{\text{max}} \), then the \( \frac{dH}{d\tau} = f(\tau) \) is transformed to linear one, namely: \( \frac{dH}{d\tau} = \psi(1/H) \), and the intersection of graphic representation of that function with abscissa allows determination of \( H_{\text{max}} \). The difference in values of the height of liquid rise determined in such a way and of that determined by direct measuring is not more than 4-6%.
1 — sample of capillary-porous structure; 2 — pilot pin; 3 — clamps; 4 — sensors; 5 — seal; 6 — chamber; 7 — boot; 8 — cover; 9 — level of liquid; 10 — burette; 11 — valve; 12 — level indicator; 13 — digital voltmeter.

Fig. 3.1.1 — Schematic drawing of pilot unit of IPMS for examination of the effect of characteristics of capillary-porous structures on the height and velocity of capillary rise of liquids.
Fig. 3.1.2 — Test unit of IPMS for examination of hydrodynamic characteristics of capillary-porous structures.
For the quantitative description of the kinetics of capillary impregnation it is necessary to know wetting angle of material with work liquid. For porous material with known structure-hydrodynamic characteristics the wetting angle $\alpha$ can be determined from simple relationship:

$$
\cos \alpha_2 = \sigma_1 \cdot \rho_2 \cdot H_{\text{max}2} \cdot \cos \alpha_1 \, / \, \sigma_2 \cdot \rho_1 \cdot H_{\text{max}1},
$$

(3.1.6)

where index 1 relates to the properties of standard (with known wetting angle) liquid, while index 2 relates to the properties of the liquid under examination. The wetting angles have been measured, in particular, in [1, 7] where it was also shown that when moving liquid against gravity the most efficient are porous structures with maximum permeability and minimum effective pore size. Estimation of the rate of capillary impregnation of metal-fiber structures located under some angle to horizon ($\phi = 15^\circ$, partial effect of gravity) by making use of analytical equation (3.1.4) gives good results.

Results of hydrodynamic properties investigation of fiber and fiber-powder capillary structures are shown in the tables 3.1.1 and 3.1.2.

Table 3.1.1.

**Hydrodynamic characteristics of metal-fiber structures developed at IPMS for using in heat pipes (work liquid – ethanol)**

<table>
<thead>
<tr>
<th>Material</th>
<th>Porosity, $\Theta$, %</th>
<th>Effective diameter of pores, D_{eff}, \mu m</th>
<th>Permeability coefficient, $K \cdot 10^{11}$, cm$^2$</th>
<th>Height of capillary rise $H_{\text{max}}$, mm</th>
<th>Criterion of transport capability $K/D_{eff}10^2$, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>59,0</td>
<td>60,0</td>
<td>2,5</td>
<td>311</td>
<td>41,7</td>
</tr>
<tr>
<td></td>
<td>61,2</td>
<td>59,0</td>
<td>5,6</td>
<td>&gt; 480</td>
<td>94,9</td>
</tr>
<tr>
<td></td>
<td>70,0</td>
<td>55,0</td>
<td>7,3</td>
<td>&gt; 480</td>
<td>132,7</td>
</tr>
<tr>
<td></td>
<td>79,0</td>
<td>60,0</td>
<td>5,5</td>
<td>&gt; 480</td>
<td>91,6</td>
</tr>
<tr>
<td></td>
<td>79,2</td>
<td>125,0</td>
<td>33,5</td>
<td>290</td>
<td>268,0</td>
</tr>
<tr>
<td></td>
<td>79,4</td>
<td>83,5</td>
<td>18,8</td>
<td>355</td>
<td>225,1</td>
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<tr>
<td></td>
<td>80,0</td>
<td>92,0</td>
<td>15,5</td>
<td>362</td>
<td>168,5</td>
</tr>
<tr>
<td></td>
<td>88,5</td>
<td>156,0</td>
<td>45,2</td>
<td>180</td>
<td>289,7</td>
</tr>
<tr>
<td></td>
<td>90,0</td>
<td>110,0</td>
<td>25,5</td>
<td>270</td>
<td>231,8</td>
</tr>
<tr>
<td></td>
<td>95,0</td>
<td>198,0</td>
<td>48,3</td>
<td>---</td>
<td>243,9</td>
</tr>
</tbody>
</table>
Table 3.1.2

**Hydrodynamic characteristics of stainless steel fiber-powder compositions**

<table>
<thead>
<tr>
<th>Material</th>
<th>Compositions, porosity, %</th>
<th>Average hydraulic diameter of pores, μm</th>
<th>Permeability coefficient K · 10^{12}, m²</th>
<th>Height of capillary rise of ethanol in one hour, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibers layer ∅ 50 μm, thickness 1 mm</td>
<td>78</td>
<td>50</td>
<td>55</td>
<td>70</td>
</tr>
<tr>
<td>Fibers layer ∅ 30 μm, thickness 1 mm</td>
<td>78</td>
<td>45</td>
<td>50</td>
<td>90</td>
</tr>
<tr>
<td>Fibers layer ∅ 50 μm, thickness 0,75 mm; fibers layer ∅ 30 μm, thickness 0,25 mm</td>
<td>67</td>
<td>30</td>
<td>20</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>78</td>
<td>32</td>
<td>25</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>88</td>
<td>36</td>
<td>32</td>
<td>70</td>
</tr>
<tr>
<td>Fibers layer ∅ 50 μm, thickness 1 mm filled by powder particles (80-100 μm) on the depth 0,25 mm</td>
<td>70</td>
<td>25</td>
<td>17</td>
<td>180</td>
</tr>
<tr>
<td></td>
<td>81</td>
<td>28</td>
<td>21</td>
<td>160</td>
</tr>
<tr>
<td></td>
<td>86</td>
<td>31</td>
<td>26</td>
<td>115</td>
</tr>
<tr>
<td>Fibers layer ∅ 30 μm, thickness 1 mm filled by powder particles (&lt;40 μm) on the depth 0,25 mm</td>
<td>70</td>
<td>20</td>
<td>12</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>23</td>
<td>17</td>
<td>130</td>
</tr>
<tr>
<td></td>
<td>86</td>
<td>26</td>
<td>22</td>
<td>100</td>
</tr>
</tbody>
</table>
3.2 EXPERIMENTAL DETERMINATION AND CALCULATION OF THERMOPHYSICAL PARAMETERS OF CAPILLARY STRUCTURES FOR PILOT BATCH OF HEAT PIPES (IPMS, MRC)

3.2.1 HP Heat-resistant

As is well known, the main design parameters for heat pipes are the following: (i) ultimate heat flux $Q_{\text{hp}}$ (in watts) which is transmitted by heat pipe, and (ii) total thermal resistance $R_{\text{hp}}$ (in K/W) of heat pipe. Total thermal resistance of heat pipe is the sum of particular thermal resistances to heat flux when supplying and removal of heat to/from heat pipe.

The process of heat transfer by heat pipe from external surface of evaporator to external surface of condenser can be divided into few steps, namely:
— heat supply from external source;
— heat transfer due to heat conductivity in a radial direction through the casing of heat pipe;
— heat transfer due to heat conductivity through wetted wick;
— heat transfer due to heat conductivity in axial direction over the casing of heat pipe;
— vapor generation;
— heat transfer due to vapor (molar mode) from the zone of heat supply to zone of heat removal due to pressure difference;
— heat transfer in the course of vapor condensation in the zone of heat removal etc.

When considering the heat pipe as heat transferring element of energetic system, one can specify its own thermal resistance $R_{\text{hp}}$ (or thermal conductivity). According to the mode of functioning and sequence of processes, the quantity $R_{\text{hp}}$ (without taking into consideration of heat transfer over the pipe casing) is a sum of thermal resistances to heat transfer through the heat pipe case wall in zones of evaporation ($R_{\text{evap}}^{w}$) and condensation ($R_{\text{cond}}^{w}$), to heat exchange in evaporation zone ($R_{\text{evap}}$), to heat exchange in condensation zone ($R_{\text{cond}}$), as well as of thermal resistance in steam line ($R_{\text{sl}}$) inside heat pipe:

$$R_{m,m} = R_{u}^{cm} + R_{u} + R_{n} + R_{k} + R_{k}^{cm}$$  \hspace{1cm} (3.2.1)

or

$$\Delta T_{m,m}/Q = (\Delta T_{u}^{cm} + \Delta T_{u} + \Delta T_{n} + \Delta T_{k} + \Delta T_{k}^{cm})/Q$$  \hspace{1cm} (3.2.2)
The thermal resistances $R_{\text{evap}}$ and $R_{\text{cond}}$ are determined by known methods of the theory for heat conductivity. The quantity $R_{\text{sl}}$ which is caused by pressure drop in steam line of heat pipe is calculated based on the curve for vapor pressure of heat carrier through hydrodynamic resistance to vapor flux. For cryogenic and low-temperature heat pipes, the value of $R_{\text{sl}}$ is as a rule negligible. So, the calculation of thermal resistance of heat pipe turns to determination of resistances $R_{\text{evap}}$ and $R_{\text{cond}}$:

$$R_u = \frac{\Delta T_u}{Q} = \frac{1}{\alpha_u F_u}; \quad R_x = \frac{\Delta T_x}{Q} = \frac{1}{\alpha_x F_x},$$

where $\Delta T_{\text{evap}}$ and $\Delta T_{\text{cond}}$ are temperature drops between vapor and inner surface of heat pipe casing in zones of evaporation and condensation, respectively; $\alpha_{\text{evap}}$ and $\alpha_{\text{cond}}$ are coefficients of heat exchange in zones of evaporation and condensation, respectively, for regime of normal functioning of heat pipe.

The heat exchange in evaporation zone of heat pipe is characterized as a rule by occurring of two regimes, namely: evaporation and boiling. In an evaporation regime the heat exchange occurs by heat conductivity through saturated liquid of capillary structure, and then by evaporation of liquid from the surface of capillary structure, which fronts to steam line.

The coefficient of heat transfer $\alpha$ in zone of heat supply (boiling of work liquid-carrier) of heat pipe is determined by experiment because of complexity in theoretical calculation.

Shown in Fig. 3.2.1 is experimental unit of IPMS for determination of heat-transfer coefficients upon boiling liquid heat carrier under conditions specific for operation of heat pipes.

Fig. 3.2.1 — Experimental unit for study thermophysical processes of vapor formation under conditions specific of heating zone of heat pipes.
3.2.2 Calculation of maximal heat-transfer capacity of heat pipe

To calculate maximal heat-transfer capacity of heat pipe the formula in [1, 7] has been used, which accounts for title of heat pipe with respect to horizon and therefore effect of gravity on $Q_{\text{max}}$:

$$Q_{\text{max}} = r \cdot \left( \frac{4 \cdot \sigma \cdot \cos \Theta}{D_{\text{eff}}} - \rho_{\text{ж}} \cdot g \cdot \sin \phi \right) / L \left[ (\mu_{\text{ж}} / K_{\text{кс}} \cdot F_{\text{кс}} \cdot \rho_{\text{ж}}) + (32 \cdot \mu_{\text{n}} / d_{\text{n}}^2 \cdot F_{\text{n}} \cdot \rho_{\text{n}}) \right]. \quad (3.2.4)$$

where indices $l$, $cs$, $sl$, and $v$ denote “liquid”, “capillary structure”, “steam line”, and ”vapor”, respectively.

It should be noted that calculation by formula (3.2.4) is correct only under assumption about complete saturation of capillary structure of heat pipe with liquid. In real conditions for heat pipe operation (especially with high-porous capillary structures) there is partial drying of capillary structure (in case of displacement of cooling zone above heating zone). In that case the real values of $Q_{\text{max}}$ will be less than calculated ones, and this fact have to be accounted in designing of heat pipes.

To calculate $Q_{\text{max}}$ by formula (3.2.4) it is necessary to know the value of permeability coefficient $K_{\text{cs}}$ which for specific capillary porous structures can be determined by experiment. We have determined those values in experiments with hydrodynamic unit of IPMS, which is a part of test stand.

For performing specific task, we developed Calculation program by making use of computer language “PASCAL”. The values of quantities in (3.2.4) were varied in the following ranges:

1. Liquid heat carrier distilled water.
2. Calculation temperatures, $T$ 80-120 °C.
3. Diameter of pores (effective), $D_{\text{eff}}$ 10-65 μm.
4. Diameter of vapor channel, $d_{\text{sl}}$ 4-8 mm.
5. Heat of vaporization, $r$ 2200-2300 kJ/kg.
6. Liquid density, $\rho_l$ 940-970 kg/m³.
7. Vapor density, $\rho_v$ 0.11-0.29 kg/m³.
8. Surface tension coefficient, $\sigma$ (55-62.5)⋅10⁻³ N/m.
9. Wetting angle, $\theta$ 10-75 °.
10. Length of heat pipe, \( L \) 500 mm.

11. Dynamic coefficient of liquid viscosity, \( \mu_l \) (2300-3510)\( \times \)10\(^{-7}\) Pa⋅sec.

12. Dynamic coefficient of vapor viscosity, \( \mu_v \) (113-128)\( \times \)10\(^{-7}\) Pa⋅sec.

13. Cross section area of capillary structure, \( F_{cs} \) (7-13.5)\( \times \)10\(^{-6}\) m\(^2\).

14. Area of vapor channel (steam line), \( F_{sl} \) (12.5-50)\( \times \)10\(^{-6}\) m\(^2\).

15. Coefficient of permeability of capillary porous structure, \( K_{cs} \) (20-100)\( \times \)10\(^{-11}\) m\(^2\).

16. Title angle of heat pipe, \( \phi \) 0-90°.

The values of \( Q_{\text{max}} \) calculated by formula (3.2.4) for pilot heat pipes (capillary porous structure – non-oxidized stainless steel, temperature 100 °C) are presented in Table 3.2.1.

### Table 3.2.1

**Values of** \( Q_{\text{max}} \** transferred by heat pipes with metal-fiber capillary structures for different diameters of heat pipe casing and angles of arrangement of heat pipe relative horizon**

<table>
<thead>
<tr>
<th>Tilt angle of heat pipe ( \phi ), degree</th>
<th>( \delta_{cs} = 0.5 \text{ mm}; \text{ porosity of capillary structure } \Theta, % )</th>
<th>( \delta_{cs} = 0.5 \text{ mm}; \text{ porosity of capillary structure } \Theta, % )</th>
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<td>+ 90</td>
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Fig. 3.2.2 — Effect of tilt angle on heat-transfer capacity of heat pipe. Outer diameter of heat pipe, mm: A – 6, B – 10; porosity of capillary structure, Θ, %: 40, 60, and 80, respectively; thickness of metal-fiber capillary structure δcs = 0.5 mm.
### 3.2.3 Calculation of heat-transfer coefficient in heating zone of heat pipe

As the results of experiment showed, the intensity of heat transfer upon boiling depends on a number of physical and geometrical characteristics of capillary-porous structures, in particular: thickness $\delta_{cs}$, heat conductivity $\lambda_{cs}$, porosity $\theta$, and effective (average) pore diameter $D_{eff}$. The comprehensive studies have been carried out at IPMS on the heat exchange upon boiling at the surfaces with metal-fiber capillary-porous structures under conditions specific of heat pipe operation, i.e. with capillary transport of liquid in the heating zone. The formula summarizing the results obtained is the following:

$$\alpha = c \cdot q^{0.6} \cdot \delta_{kc}^{m} \cdot \lambda_{kc}^{0.25} \cdot (1 - \Theta_{max} / 1 - \Theta)^{0.15} \cdot D_{eff}^{0.1} \cdot \left( \frac{\lambda_{ж}^2}{\nu_{ж} \cdot \sigma \cdot T_{нас}} \right)^{0.333},$$  \hspace{1cm} (3.2.5)

where $c = 200, m = 0.65$ with $0.4 \cdot 10^{-3} \leq \delta_{cs} \leq 1.2 \cdot 10^{-3}$ m; $c = 0.5, m = - 0.2$ with $1.2 \cdot 10^{-3} \leq \delta_{cs} \leq 9.0 \cdot 10^{-3}$ m; index “sat” denotes saturation.

The quantities are presented in CI system. The thickness $\delta_{cs}$ is specified upon calculation. The carcass heat conductivity of metal-fiber capillary structure is determined by formula in [7]. To determine heat conductivity, it is necessary to know heat conductivity of original metallic fibers-fractions, their length and diameter. The values of porosity $\Theta$ and $\Theta_{max}$ are specified and calculated quantities, and these are determined by empirical formulae in [7]. The set of parameters suggested by Labuntsov, namely $\left( \frac{\lambda_{ж}^2}{\nu_{ж} \cdot \sigma_{sat} \cdot T_{нас}} \right)^{0.333}$, accounts for the effects of thermophysical properties of liquid.

Shown in Figs. 3.2.3 and 3.2.4 are the results of experimental study of heat exchange intensity upon boiling distilled water on the surfaces with copper metal-fiber structures under conditions of capillary transport at atmospheric pressure. We have examined the metal-fiber structures of medium and high porosity ($\Theta = 40$ and $80\%$). The thickness of metal-fiber capillary structures was varied in the range $\delta_{cs} = 0.4$-9.0 mm. Thus, the real range of thicknesses of capillary structures in heat pipes has been studied.
Porosity $\Theta = 40\%$; thickness of capillary structure $\delta_{cs}$, mm: 1 – 0.2, 2 – 0.4, 3 – 0.8, and 4 – 4.0. Curves I-IV reflect calculations for specified thicknesses, respectively, and curve V reflects calculation for boiling of water on smooth technical surface.

Fig. 3.2.3 — Comparison of experimental data and results of calculation (by formula (3.2.5)) for heat-transfer coefficients upon boiling water on surfaces with metal-fiber capillary structures of medium porosity under conditions of capillary transport of liquid (regime of heat pipe).

Thickness of capillary structure $\delta_{cs} = 0.8$ mm; porosity $\Theta$, %: 1 – 40, 2 – 70, and 3 – 84. Curves I-III reflect calculations for specified porosities, respectively, and curve IV reflects calculation for boiling of water on smooth technical surface.

Fig. 3.2.4 — Comparison of experimental data and results of calculation (by formula (3.2.5)) for heat-transfer coefficients upon boiling water on surfaces with metal-
fiber capillary structures of high porosity under conditions of capillary transport of liquid (regime of heat pipe).

The curves I-IV in Figs. 3.2.3 and 3.2.4 have been obtained by calculation for values of thickness of metal-fiber capillary structures pointed in figure captions. The results of comparison experimental data (points 1-4) and calculations (curves I-IV) in Figs. 5 and 6 show satisfactory accuracy of assumed empirical formula (3.2.5). The spread of experimental points in plots $\alpha = f (q)$ is not more than $\pm 20\%$, and this value is appropriate for boiling tests.

4.1 DEVELOPMENT OF FIBER-POWDER CAPILLARY STRUCTURES (IPMS)

The research carried out earlier within current project has revealed the fact that for using in HP the most promising are materials prepared as highly permeable and strong fibrous carcass that contains one or few thin fiber-powder layers thus providing intensification of both heat transfer and mass transfer. The macro-structure of fibrous carcasses with powder and without it are shown in Fig. 4.1.1.

The CSs were manufactured by co-forming and sintering of thin highly porous fiber and powder layers with dimensions of (1-5)×100×500 mm followed by free upsetting of sintered plate to specified porosity. As initial materials, the fibers of stainless steel (KH18N9T grade) of 30 $\mu$m and 50 $\mu$m in diameter and 3 mm in length, and also powders of the same steel with particle size of 40 $\mu$m and 80 $\mu$m have been used.

The flat CSs were formed at special vibrating unit which allowed successive layer-by-layer deposition of fibers and powder particles onto flat substrates which moved reciprocally.

The technique for forming developed by project authors allows making various structures as alternating thin highly porous fiber and powder layers, and also highly porous and strong fibrous carcass partly or completely filled with powder [8].
After forming, the billets for CS are subjected to sintering (strengthening heat treatment). During sintering, the good inter-particle contacts form which are responsible for physicomechanical characteristics of CS.

To prevent harmful effects of oxygen and moisture, sintering of the CS was performed in a vacuum [9]. The quality of inter-particle contacts in CS, apart of other factors, is determined by the fact that thin fiber and powder layers are subject to different in magnitude deformation changes during sintering. To suppress negative effect from different degree of shrinkage of fibers and powder particles upon sintering, we applied low static loads (15-50 g/cm²).

The plots for quality of inter-particle contacts in highly porous fibrous carcasses sintered at different temperatures in a vacuum are presented in Fig. 4.1.2. As seen, the quality of contacts increases with increasing sintering temperature, decreasing fiber diameter and deformation extent after annealing.
1 – specimen made of fibers of 30 μm in diameter, porosity 90%; 2 — specimen made of fibers of 30 μm in diameter, rolled to porosity 80% and re-sintered; 3 — specimen made of fibers of 30 μm in diameter, rolled to porosity 70%; 4 — specimen made of fibers of 50 μm in diameter, rolled to porosity 80%; 5 — specimen made of fibers of 50 μm in diameter, rolled to porosity 70%.

Fig. 4.1.2 — Dependence of contact quality in highly porous specimens made of stainless steel on sintering temperature.

After sintering, the fiber-powder CSs were subjected to free upsetting to prespecified porosity. The process of free upsetting (densification) of sintered fibers can be conventionally divided in three stages. In the 1st stage, the densification of fibers occurs mainly due to bending of them, and the upsetting extent sharply increases with increasing pressure. In the 2nd and 3rd stages, when deformation due to fiber bending decreases and local contact plastic deformation eventually passes through the whole bulk, the deformability of fibrous materials decreases. For materials made of metal powders exhibiting purely contact densification nature the process of free upsetting occurs in two stages. In this case, in the 1st stage the densification occurs due to local contact plastic deformation while in the 2nd stage it occurs due to plastic flow of the whole material.

The dependence of upsetting extent for fibrous and fiber-powder porous specimens on pressure is shown in Fig. 4.1.3.
1 — deformation curve for specimen made of fibers 50 μm in diameter; 2 — deformation curve for composite specimen consisting of fibers 50 μm in diameter and powder with particle size of 100 μm; 3 — deformation curve for specimen made of powder with particle size of 100 μm.

As seen in Fig. 4.1.3, the observed deformation in tested specimens agree well with known ideas about the densification mechanisms for fibers and powders [10]. The specimens made of fibers, which were subject to contact as well as plastic bending deformation upon densification exhibited much more deformability than powder specimens with purely contact densification nature. In fiber-powder specimens the two aforementioned mechanisms take place.
4.2 DEVELOPMENT AND MANUFACTURE OF HEAT PIPES WITH CAPILLARY STRUCTURES MADE OF METAL FIBERS AND POWDERS (IPMS, GERI)

The production procedure for manufacturing HP with CS made of metal fibers and powders includes a series of operations (Fig. 4.2.1) the most important of which are the following:

- preparation of flat CS with specified structure and physicomechanical characteristics;
- application of flat CS onto inner surface of cylindrical or rectangular casing of HP.

![Technological scheme for manufacturing HP with CS made of metal fibers and powders.](image)

The techniques for joining thin flat CS with HP casing have been developed at the IPMS, which provided good contact between CS and casing. Owing to those techniques the hydrodynamic and structural characteristics of CS do not deteriorate.

The most rational technique for introducing flat CS into HP’s casing is that in which the operation of application of CS to the inner surface of casing is carried out as follows. First, the flat CS is shaped into cylinder or rectangular by upsetting onto rod of respective shape and dimensions (co-drawing of the rod with CS in elastic case through the draw plate). Thus, the
friction of CS on the inner surface of draw plate is eliminated and CS is produced with uniform thickness. The upsetting rod is a cylindrical or rectangular bar of stainless steel covered with aluminum oxide. After drawing of CS through the drawing plate, the CS can be introduced into the casing of HP together with upsetting rod or without it.

The reliable contact of highly porous body with compact body is of prime importance for HP performance. So, special attention was paid to studying the liquid-phase and solid-phase sintering of high-porous CS with HP casing. The objects for investigation were specimens made of copper and corrosion-resistant steel which modeled contact of porous permeable body with compact body and consisted of two flat billets (high-porous and pore-free) (Fig. 4.2.2).

Fig. 4.2.2 — Schematic drawing of specimen to model contacts of permeable bodies with compact ones: 1 — compact substrate; 2 — sintering zone; 3 — porous billet.

The results of testing strength and electrical conductivity of CS with different state of sintered surfaces are shown in Fig. 4.2.3.

Fig. 4.2.3 — Dependence of electrical conductivity (□) and strength (■) of copper specimens on the preparation quality of initial materials.

1 — initial state of tested materials; 2 — materials oxidized at 400 °C; 3 — materials cleansed of lubricant; 4 — materials cleansed of lubricant and oxides; 5 — ultrasonically cleansed materials.
It is seen from Fig. 4.2.3 that the quality of sintering is affected strongly by the cleaning extent of surfaces in contact. Only thorough degreasing with acetone and ethanol of initial materials provides increase in conductivity and strength of specimens by 19% and 85%, respectively. However, the most efficient is ultrasonic treatment of materials in an acetone. After such treatment the electrical conductivity increased by 60% and the strength increased by a factor of 2 to 3.

The tests revealed also that strength of joint after solid-phase sintering is less then that for high-porous billet even for specimens pre-treated ultrasonically and then sintered following to the optimum sintering regime. An increase in the strength of inter-particle contacts is achieved by liquid-phase sintering of porous body with compact one. In this case, the amount of liquid phase has to be at a minimum because porous fibrous materials exhibit high capillary properties and suck in liquids intensively.


Fig. 4.2.4 — Dependence of electrical conductivity and strength on coating thickness for copper specimens.

It is seen from Fig. 4.2.4 that intermediate coatings made of silver and tin increase the strength of copper specimens by a factor of about 4. In this case, the main increase in
strength and electrical conductivity of joints is for thin coatings when formed liquid phase fills the pores only in the zone of adjoin porous body with compact one.

Due to investigations carried out, the optimum techniques have been developed for manufacturing HP with fiber-powder CS having specified hydrodynamic and structure characteristics (Fig. 4.2.5 and Table 4.2.1).

Fig. 4.2.5 — Appearance of heat pipes with fiber-powder capillary structures.

### Table 4.2.1

<table>
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<tr>
<th>№</th>
<th>Mass of HP, g</th>
<th>Diameter, mm</th>
<th>Length with exhaust tube, mm</th>
<th>Mass, g</th>
<th>Thickness, mm</th>
<th>Length, mm</th>
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4.3 PRELIMINARY TESTING OF HEAT PIPES (MRC)

4.3.1 Experimental unit for testing work characteristics of heat pipes

To study thermophysical parameters of HP, the special unit has been designed in which the angle of HP tilt with respect to horizon can be varied in the range 0-180°. The HP is heated by special heater, and the heat is removed from condensation zone by air or liquid cooling. The temperature over the HP length is measured with thermocouples. The HP prepared for standard tests is shown in Fig. 4.3.1.1.

Fig. 4.3.1.1 — Schematic drawing of HP prepared for thermophysical tests. 2-10 – thermocouples.

The test unit consists of: i) the system for supply, control and measurement of power of heat flux; ii) system for high-accurate measurement of temperature in check points of HP; iii) system for measurement of heat removal parameters; iii) some subsidiary systems.

The test unit is shown in Fig. 4.3.1.2.

Fig. 4.3.1.2 — Unit for thermophysical tests of heat pipes.

Shown in Fig. 4.3.1.3 is HP prepared for testing.
Fig. 4.3.1.3 — Pilot HP prepared for thermophysical tests.

Upon testing, the HPs were tilted at various angles with respect to horizon by special platform (Fig. 4.3.1.4).

Fig. 4.3.1.4 — Appliance for tilting HP with respect to horizon.
4.3.2 Preliminary results of testing heat pipes

The technique for testing HP was worked out with HP having CS sintered of
discrete fibers of 50 μm in diameter and 3 mm in length. The thickness of CS was 0.8 μm
and porosity 80%.

The results of experiments are presented as plots for dependence of temperature in
each check point on casing of test HP on testing time.

The typical dependence $T_x=f(\tau)$ is shown in Fig. 4.3.2.1. HP is in horizontal location.

![Temperature variation in check points of HP with test time. 1—before heater; 2 — after heater; 3 — before radiator; 4 — after radiator.](image-url)
Table 4.3.2.1

Lists the results of testing HP

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<td>15°</td>
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<td>104,00</td>
<td>20°</td>
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<td>112,00</td>
<td>30°</td>
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<td>31</td>
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<td>2</td>
<td>13</td>
<td>1</td>
<td>119,00</td>
<td>15°</td>
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<td>Horizontal displacement of HP</td>
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<tr>
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<td>31</td>
<td>29</td>
<td>26</td>
<td>5</td>
<td>7</td>
<td>2</td>
<td>127,00</td>
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</tr>
</tbody>
</table>

Table 4.3.2.2

Results of testing pilot HP

<table>
<thead>
<tr>
<th>Date</th>
<th>t1, oC</th>
<th>t2, oC</th>
<th>t3, oC</th>
<th>t4, oC</th>
<th>t5, oC</th>
<th>Δt1</th>
<th>Δt2</th>
<th>Δt3</th>
<th>Time, h</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>41</td>
<td>37</td>
<td>31</td>
<td>29</td>
<td>25</td>
<td>4</td>
<td>7</td>
<td>2</td>
<td>133,00</td>
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</table>

Shown in Fig. 4.3.2.2 is temperature variation in check points of HP vs. test duration.
Fig. 4.3.2.2 — Variation of temperature over the length of HP depending on test duration: 1 — before heater; 2 — after heater; 3 — before radiator; 4 — after radiator.

The results of testing HP under conditions of free convection (cooling fan switched-off) and forced cooling by ambient air (cooling fan switched-on) are presented in Fig. 4.3.2.3.

Fig. 4.3.2.3 — Temperature variation in check points of horizontally located HP under free convection of air that cools the heat-removal zone of HP (fan switched-off) and forced motion of cooling air (fan switched-on). 1 — before heater; 2 — after heater; 3 — before radiator; 4 — after radiator.
The results presented in Fig. 4.3.2.3 show that with switched-on fan of the system for air cooling the HP (with steady transferred heat flux $Q$) reaches stationary heat regime (under which the main thermophysical characteristics of HP are tested) much faster. This is important for future tests of pilot HPs.

In Fig. 4.3.2.4 the original data are presented concerning influence of tilt angle if HP on temperature variation in check points over the length of HP. These results have to be checked with multiply repeated tests of large amount of HPs.

![Graph showing temperature variation](image)

**Title angle of HP with respect to horizon, deg**

**Temperature, °C**

Fig. 4.3.2.4 — Temperatures in check points over the length of HP vs. tilt angle of HP with respect to horizontal location.

To evaluate preliminary the influence of characteristics of new CS on thermophysical and hydrodynamic parameters of HP based on fiber-powder materials developed, we have carried out tests aimed to determination of values of ultimate heat fluxes for two HPs performing under the most sever conditions, i. e. with movement of liquid heat carrier against gravity (vertical location of HP with upper location of heating zone). The results obtained confirmed the idea about improvement of capillary-transport characteristic of new HPs in comparison with traditional HPs based on fiber structures, in particular when performing under conditions when liquid moves against gravity. Table 4.3.2.1 lists the results obtained. For comparison, we give also the values for ultimate heat flux for two HPs made with only fibrous CS. All the HPs had similar main work parameters and differed in CS type.

So, within the framework of INTAS project № 06-1000024-9339 the pilot batch of HPs with new capillary structures made of metal fibers and powders have been
manufactured. The unit has been made ready for testing thermophysical characteristics of HP under on-land conditions. The techniques for testing HP have been worked out, and the values of ultimate heat fluxes for two HPs based on developed fiber-powder CS determined.

Table 4.3.2.3

<table>
<thead>
<tr>
<th>Characteristics of HP (liquid is water)</th>
<th>Type of CS</th>
<th>Porosity of CS θ, %</th>
<th>Thickness of CS δ, mm</th>
<th>Sinuosity of porous channels, B</th>
<th>Equilibrium hydraulic pore diameter $D_{hydr}$, μm</th>
<th>Length of HP L, m</th>
<th>Length of HP’s transport zone of, m</th>
<th>Maximum heat flux $Q_{max}$, W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber 50 μm in diameter</td>
<td>76,8</td>
<td>0,45</td>
<td>1,13</td>
<td>54</td>
<td>0,25</td>
<td>0,1</td>
<td>11,7</td>
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<tr>
<td>Fiber 50 μm in diameter</td>
<td>76,8</td>
<td>0,45</td>
<td>1,13</td>
<td>54</td>
<td>0,25</td>
<td>0,06</td>
<td>10,2</td>
<td></td>
</tr>
<tr>
<td>Fiber 50 μm in diameter + powder with particles 80 μm</td>
<td>85</td>
<td>0,8</td>
<td>1,2</td>
<td>28</td>
<td>0,30</td>
<td>0,1</td>
<td>15,9</td>
<td></td>
</tr>
<tr>
<td>Fiber 50 μm in diameter + powder with particles 80 μm</td>
<td>74</td>
<td>1,0</td>
<td>1,2</td>
<td>23</td>
<td>0,30</td>
<td>0,1</td>
<td>13,7</td>
<td></td>
</tr>
</tbody>
</table>
CONCLUSIONS

1. Fiber CS provide better hydrodynamic properties than layer fiber and skeleton fiber-powder CS (under equal porosity has permeable coefficient in 2.3–2.5). These results may be explained better with the fact that maximum permeability available of powder materials is not higher than 60% (not including usage of special technologies for obtaining high porosities), as in fiber materials porosity of 80–85% is easily obtained.

2. Fiber powder CS are less effective in permeability than fiber CS, as they possess pores 1.8–2.5 times smaller size, which provides better transportation abilities. Combined CS made from 50 mkm diameter fibers and 80–100 mkm dispersity powder, possess better union of permeability and pore size (comparing to fiber materials filled with powder particles of lesser size).

3. Proposed the following parameters for pilot batch of heat pipes, namely: length 0.5 m; stainless steel and copper as materials for casing and capillary structure; porosity of capillary structure 60-90%; thickness of capillary structure 0.5-1.0 mm; liquid heat carrier – distilled water.

4. The pilot batch of HPs with new capillary structures made of metal fibers and powders have been manufactured.
REFERENCES