ARTERIAL MINIATURE HEAT PIPES

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Abstract

The purpose of the present research was increasing of heat transfer capacity of conventional miniature heat pipes. Design of the miniature heat pipe with an arterial powder capillary structure has been developed. The expressions for calculation of optimum quantities of capillary structure design parameters are obtained. Two miniature heat pipes "copper-water" have been made and tested. The results of the tests show, that use of arteries allows to increase considerably the heat transfer capacity of miniature heat pipes.

KEYWORDS

miniature heat pipe, heat transfer limit, powder capillary structure.

INTRODUCTION

The effective heat transfer and maintenance of thermal modes of various systems and equipment is an urgent problem of modern engineering. The problem of thermal control of electronic elements having the tendency of miniaturization and corresponding increase of specific heat energy evolving is especially urgent. For example, metal oxide semiconductor controlled thyristors can dissipate up to 300 W/cm^2 [1]. In complete evaluation of the qualities of one or another cooling system important parameters except for heat transfer characteristics are also: mass, size, simplicity of positioning and cost. From this point of view miniature heat pipes of conventional type have indisputable advantage before other cooling systems. Use of miniature heat pipes with cross size limited by meaning of 3 - 4 mm for cooling elements of telecommunication systems and PC components were begun 15 years ago [2].

Zhuang et al. [3] have made comparison of heat transfer performance of miniature heat pipes with three different capillary structures: sintered, mesh and fiber. At length of heat pipes of 150 mm, outside diameter of a case of 3 mm, thickness of a wall of the case of 0,3 mm the heat transfer capacity of the investigated heat pipes didn't surpass 10 W in the most favorable orientation (evaporator is above).

Kim et al. [4] have tested miniature heat pipes with woven-wired wick. At length of the heat pipe of 300 mm, outside diameter of the case of 4 mm, length of evaporation zone of 40 mm and condensation zone of 53 mm the strong dependence of heat transfer capacity from an inclination angle of the heat pipe was observed. In horizontal orientation the heat transfer limit made 22 W, at inclination angle -5° it made 12 W.

The simplest way of increase of miniature heat pipe heat transfer capacity is creation of capillary structure with pore size decreasing in the direction of evaporation zone [5,6]. This way has shown its efficiency by allowing to increase the heat transfer limit of heat pipes approximately twice at an optimum ratio of structural parameters of capillary structure. However such heat transfer capacity is also insufficient for removal of heat flux generated by modern electronic components.

Thus, the miniature heat pipes are very efficient devices for the achievement of high local heat removal rate and uniform temperatures in electronic components. However small area of capillary structure cross section causes also small heat transport capacity, especially at heat transport distance more than 200 mm. Therefore development of miniature heat pipes with high transport capacity is the urgent practical task.

DESIGN OF ARTERIAL MINIATURE HEAT PIPE

For solution of this task a design of the miniature heat pipe with an arterial powder capillary structure was developed. The design of the arterial miniature heat pipe is presented on Fig. 1. The outside diameter of the heat pipe can make a few mms. The basic feature of the design is presence in the capillary structure of a thin (diameter less than 1 mm) artery, in which condensate is delivered to evaporation zone under action of vapor pressure. To avoid the formation in the artery of vapor bubbles the artery doesn't pass through evaporation zone, and ends up some mms before it.

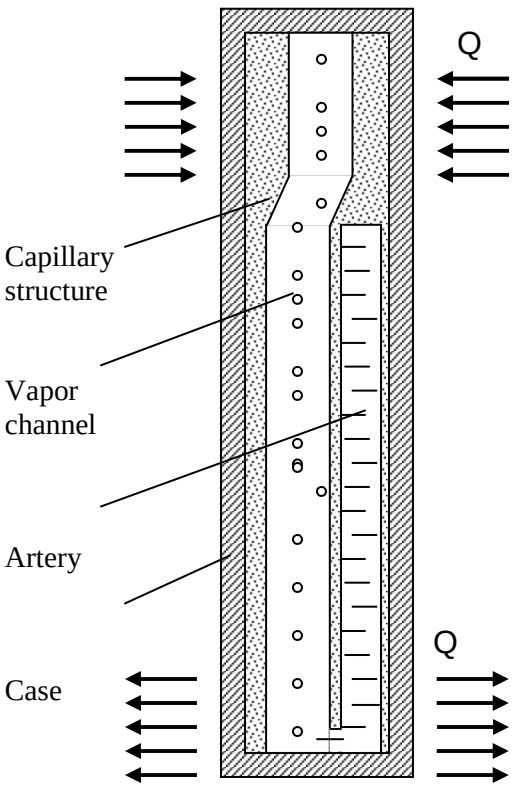

Fig. 1. Scheme of longitudinal section of miniature heat pipe

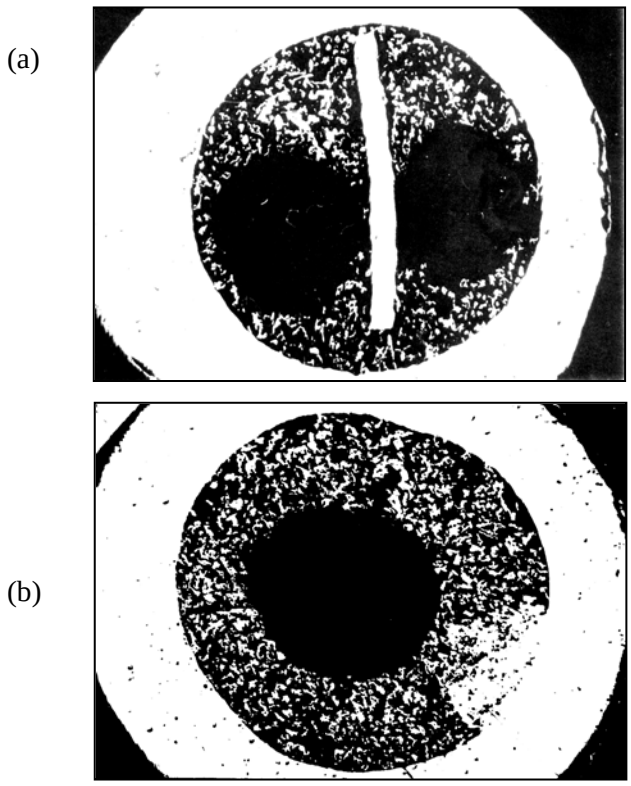

Fig. 2. Photograph of cross-section of arterial arterial miniature heat pipe in transport zone (a) and in evaporation zone (b).

Fig. 2 illustrates a variant of real device of powder arterial capillary structure. The photograph of cross-section of arterial miniature heat pipe in transport zone is presented on Fig. 2 (a), and photograph of cross-section in evaporation zone – on Fig. 2 (b). The outside diameter of the copper case is 3 mm, thickness of a wall is 0.5 mm. For reliable separation of artery and vapor channel in condensation and adiabatic zones the copper plate with thickness of 0.2 mm is used. Capillary structure is moulded and sintered from copper powder.

PHENOMENA ANALYSIS

Theoretical analysis was carried out at the following assumptions:

- the heat pipe works in the evaporation mode;
- the heat flux density is constant along evaporation and condensation zones;
- determining temperature is temperature of saturation vapor;
- liquid movement in capillary structure is laminar and obeys the Darcy's law;
- the problem is considered as one-dimensional.

The closed circulation of the heat-carrier in the heat pipe in stationary mode occurs at the expense of capillary pressure p_c, created by capillary structure and equal:

$$p_c = \frac{4\sigma \cos\Theta}{d_0}, \tag{1}$$

where σ - surface tension of the liquid heat-carrier,

Θ - corner of wetting of a material КС by the liquid heat-carrier,

d_0 - average hydraulic capillary structure pore size.

With gradual increasing heat flux the pressure losses along the vapor-liquid path increase too. The common hydraulic resistance along vapor-liquid loop includes the resistance to vapor flow in vapor channel along full length of heat pipe dp_v, the resistance to liquid flow in artery along the length of both condensation and transport zones dp_l and the resistance to liquid flow in pore space of capillary structure along the length of evaporation zone dp_{CS}. At the certain heat flux there comes such condition, when the driving pressure difference is insufficient to ensure a necessary liquid flow from condensation zone to evaporation zone. The restriction of heat pipe heat transfer capacity is caused by limited quantity of capillary pressure and determined from pressure balance along vapor-liquid loop which at the made assumptions looks as follows:

$$p_c = \Delta p_v + \Delta p_l + \Delta p_{CS} - \Delta p_g, \tag{2}$$

where

$$\Delta p_g = \rho_l g l \sin\varphi \tag{3}$$

– hydrostatic difference between the ends of heat pipe (negative at liquid movement against gravity force).

The greatest possible artery diameter d_l is determined by inside diameter of the heat pipe case d, thickness of a partition between vapor channel and artery δ and vapor channel diameter d_v:

$$D_l = D - \delta - D_v. \tag{4}$$

If heat flux transferred by heat pipe is equal Q, the vapor velocity in the vapor channel v_v is equal:

$$v_v = \frac{Q}{\gamma \rho_v S_v}, \tag{5}$$

where γ – latent heat,

ρ_v – vapor density,

$$S_v = \frac{\pi D_v^2}{4} \tag{6}$$

- cross-section area of vapor channel.

The liquid velocity in artery is equal:

$$v_l = \frac{Q}{\gamma \rho_l S_l}, \tag{7}$$

where ρ_l - density of the liquid,

$$S_l = \frac{\pi D_l^2}{4} \tag{8}$$

– cross-section area of artery.

Pressure difference in vapor phase, according to the Puazail law, is equal:

$$\Delta p_v = \frac{32\mu_v \bar{l}_v v_v}{D_v^2} = \frac{128\mu_v \bar{l}_v Q}{\pi\gamma\rho_v D_v^4}, \tag{9}$$

where μ_v - vapor dynamic viscosity,

$$\bar{l}_v = \frac{l_e}{2} + l_t + \frac{l_c}{2} \tag{10}$$

- effective transport length of the vapor channel,
l_e, l_t, l_c - accordingly lengths of evaporation, transport and condensation zones.

Pressure difference in a liquid flowing through the artery, according to Puazail law, is equal:

$$\Delta p_l = \frac{128\mu_l \bar{l}_l Q}{\pi\gamma\rho_l (D - \delta - D_v)^4}, \tag{11}$$

where μ_l - liquid dynamic viscosity,

$$\bar{l}_l = l_t + l_c \tag{12}$$

- effective transport length of artery.

Pressure difference in a liquid flowing through capillary structure, according to Darcy's law, is equal:

$$\Delta p_{CS} = \frac{Q\bar{l}_{CS}\mu_l}{k\rho_l\gamma S_{CS}}, \tag{13}$$

where

$$\bar{l}_{CS} = \frac{l_{CS}}{2} \tag{14}$$

- effective transport length of capillary structure,
l_{CS} - length of capillary structure,
k - permeability coefficient of capillary structure,
S_{CS} - cross-section area of a capillary structure porous material.

Permeability coefficient of capillary structure is connected with an average hydraulic pore size by expression [7]:

$$k = \xi d_0^{\nu}. \tag{15}$$

Substituting the expressions (3), (9), (11), (13), (15) in (2), it is possible to receive for maximum heat flux Q:

$$Q = \frac{\dfrac{4\sigma\cos\Theta}{d_0} + \rho g l \sin\varphi}{\dfrac{128\mu_v \bar{l}_v}{\pi\gamma\rho_v D_v^4} + \dfrac{128\mu_l \bar{l}_l}{\pi\gamma\rho_l (D-\delta-D_v)^4} + \dfrac{\bar{l}_{CS}\mu_l}{\xi d_0^{\nu}\rho_l\gamma S_{CS}}}. \tag{16}$$

The investigation of the received expression for heat flux concerning a maximum allows to estimate for the given heat transfer conditions optimum quantities of heat pipe design parameters: diameters of the vapor channel and artery, capillary structure pore size.

For optimum quantity of vapor channel and artery diameters it is possible to receive in consequence analytical expressions, accordingly:

$$D_v = \frac{\sqrt[5]{\frac{\mu_v \bar{l}_v}{\rho_v}}}{\sqrt[5]{\frac{\mu_v \bar{l}_v}{\rho_v}} + \sqrt[5]{\frac{\mu_l \bar{l}_l}{\rho_l}}}(D-\delta), \tag{17}$$

$$D_l = \frac{\sqrt[5]{\frac{\mu_l \bar{l}_l}{\rho_l}}}{\sqrt[5]{\frac{\mu_v \bar{l}_v}{\rho_v}} + \sqrt[5]{\frac{\mu_l \bar{l}_l}{\rho_l}}}(D-\delta). \tag{18}$$

For calculation of optimum quantity of capillary structure average hydraulic pore size d_0 one can obtain a transcendental equation:

$$\frac{512\sigma\cos\Theta}{\pi\gamma}\left(\frac{\mu_v \bar{l}_v}{\rho_v D_v^4} + \frac{\mu_l \bar{l}_l}{\rho_l D_l^4}\right) d_0^{\nu} - \frac{\rho g l \sin\varphi \bar{l}_{KS}\mu_l}{\xi\rho_l\gamma S_{KS}} d_0 + (1-\nu)\frac{4\sigma\cos\Theta \bar{l}_{KS}\mu_l}{\xi\rho_l\gamma S_{KS}} = 0. \tag{19}$$

For a case of horizontal orientation of heat pipe (φ=0) expressions for optimum quantity of capillary structure average hydraulic pore size can be obtain in analytical kind:

$$d_0 = \left(\frac{\pi(\nu-1)\bar{l}_{KS}\mu_l}{128\xi\rho_l S_{KS}\left(\frac{\mu_v \bar{l}_v}{\rho_v D_v^4} + \frac{\mu_l \bar{l}_l}{\rho_l D_l^4}\right)}\right)^{\frac{1}{\nu}}. \tag{20}$$

It is necessary to note, that the optimum quantity of vapor channel and artery diameters aren't connected with parameters of capillary structure, while the optimum quantity of the capillary structure average hydraulic pore size пор depends on diameters of vapor channel and artery.

EXPERIMENTS

In order to check the serviceability of described miniature heat pipe design two heat pipes "copper-water" was made and tested. Design parameters of heat pipes are presented in Table 1.

Table 1. Design parameters of heat pipes

Parameters	Heat pipe 1	Heat pipe 2
Outside diameter of pipe, mm	3	4
Inside diameter of pipe, mm	2	3
Total length, mm	200	300
Length of evaporator, mm	20	20
Length of condenser, mm	50	50
Diameter of vapor channel, mm	1.2	1.8
Diameter of artery, mm	0.6	1
Average pore diameter, μm	20	20

An experimental set-up to investigate the miniature heat pipes heat transfer capacity was analogous principally to the set-up described in paper [7]. Heat pipe evaporator heating was carried out with electric heaters made of Ni-Cr thermic wires wound around the wall of the case over an electric insulation. Heat losses to the ambient were minimized by covering thermic wires with multiple folds of a thermal insulation material made of glass fiber. Heat pipe adiabatic part was inserted into a

thermal insulation material made of foam plastic. Heat pipe condenser was cooled by the water flow in cooling jacket. Heat pipe surface temperature measurements were performed by thermocouples and heat pipe tilt measurements were realized by a system of the tilt deviation. The heat was supplied by an electric source and was increased until when temperature of the wall at the evaporator end increased rapidly due to capillary structure dryout.

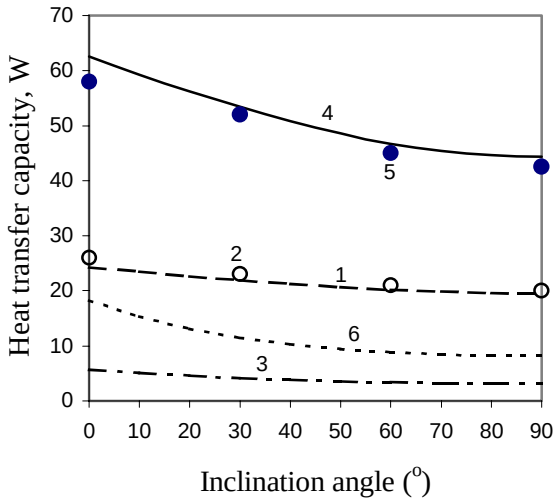

Fig. 3. Maximum heat transfer capacity of miniature heat pipes as function of inclination angle:
1 –calculation, 2 –experiment for heat pipe 1,
3 – calculation for conventional heat pipe Ø 3 mm,
4–calculation, 5 –experiment for heat pipe 2,
6 – calculation for conventional heat pipe Ø 4 mm

Results of experimental investigation of heat pipe heat transfer capacity in comparison with results of calculation are given in Fig. 3. Also here the results of calculation [5] of maximal heat transfer capacity of conventional heat pipes having the same geometrical sizes are given.

It is seen in the Fig. 3 that the heat transfer capacity of arterial miniature heat pipes is very high and surpasses considerably the heat transfer capacity of conventional miniature heat pipes. It is seen also that heat transfer capacity of arterial miniature heat pipes has much less weak dependence on the inclination angle in comparison with conventional miniature heat pipes [4]. This is because that small distance of liquid transport through the pore space allows to use capillary structure with rather small (order of 20 μm) pore size. The created capillary pressure surpasses considerably hydrostatic difference, therefore hydrostatic difference don't influences considerably work of heat pipe at inclination angle change.

CONCLUSION

Design of the miniature heat pipe with an arterial powder capillary structure is developed. The expressions for calculation of optimum quantities of capillary structure design parameters are obtained. Two miniature heat pipes "copper-water" was made and tested. The results of the tests show, that use of arteries allows to increase considerably the heat transfer capacity of miniature heat pipes.

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