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# OPEN-TYPE MINIATURE HEAT PIPES

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*The hypothesis that systems of thermoregulation, similar to open-type micro heat pipes, exist in nature (soils, living organisms, plants) and in a number of technological processes (drying, thermodynamic cycles on solid adsorbents) is considered. The hydrodynamics and heat transfer in such thermoregulation systems differ from the hydrodynamics and heat transfer in classical heat pipes, since their geometrical dimensions are extremely small (dozens of microns), adhesion forces are powerful, the effect of the field of capillary and gravitational forces is significant, and strong interaction between counter-current flows of vapor and liquid takes place.*

Miniature heat pipes, whose diameter is 30 $\mu$m - 1 mm and whose length varies within 1 - 5 mm, can be successfully applied for cooling the elements of computers, microelectronics devices, and thermoregulation systems.

The term "micro heat pipe" was suggested for the first time in 1984 by Cotter [1]. Heat pipes which have a hydraulic diameter comparable with the radius characterizing the curvature of the surface of the "liquid-vapor" interface presently have been developed by Japanese specialists in the field of computing techniques [2]. The most typical transverse dimension of such micro heat pipes is in the form of a triangle or a quadrangle with acute angles forming the slits filled by the fluid, differing in the curvature of the "liquid-vapor" interface in the evaporator and condenser.

Micro heat pipes exist in nature and play an important role in organizing the thermoregulation process in the sweat glands of animals [3], plant leaves [4], etc.

In wood drying, in sorption and desorption in fibrous adsorbents (coal fiber), and in the process of heat and mass transfer in nonisothermal wet capillary-porous media (soils), hydrodynamic and heat transfer processes in the gravitational field take place in the presence of capillary and adhesion forces, when the effects of micro heat pipes are manifested. Let us call such systems "open-type" micro heat pipes. An open-type micro heat pipe is shown schematically in Fig. 1.

Open-type micro heat pipes, in contrast to ordinary ones, are connected with the environment through porous membranes 1, 2, and the pressure on them changes weakly with changing thermal load.

It is known that for micro heat pipes $r_0/r_h = 1$, where $r_c$ is the radius of the capillary surface of the "liquid-vapor" interface, and $r_h$ is the hydraulic radius of the vapor channel of the micro pipe. For such systems the Laplace-Young law:

$$P_{v(x)} - P_{l(x)} = \sigma/r(x)$$

or its differential form

$$dP_v - dP_l = -\sigma/r^2 \frac{dr}{dx}.$$

Open-type micro heat pipes, in contrast to classical ones, can be dozens and hundreds centimeters long. In this case, the gravity field plays an important role and is commensurable in its effect with the field of capillary forces. An open-type micro heat pipe transports a portion of the liquid through porous membranes, and the rest of the liquid circulates inside the body in the form of vapor and film. The curvature of the "liquid-vapor" interface in this case be described as [5]

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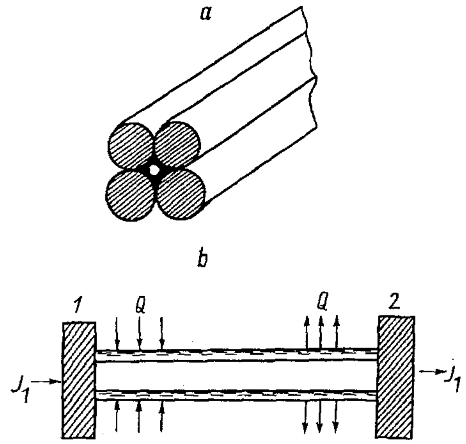


Fig. 1. Longitudinal section of the open-type micro heat pipe: 1, 2) porous membranes-hydroseals; a) transverse section of the wood fibers; b) $J_l$ is the liquid flow through porous membranes 1, 2; Q is the heat flux through the micro heat pipe.

$$K = \frac{1}{\sigma}\left[P_{vi} - P_{li} + \rho_{vi}^2 v_{vi}^2 \left(\frac{1}{\rho_{vi}} - \frac{1}{\rho_{li}}\right)\right].$$

In this equation, the first term in square brackets gives the local vapor pressure, the second the local liquid pressure, and the third the rate of radial heat transfer (kinetics of phase transition). $K < K_{max}$, where $K_{max}$ is the limit of capillary absorption:

$$\sigma K + \frac{A}{\delta_l^3} \geqslant \rho_l g L \sin\varphi + \frac{8192}{3}\,\frac{V_v m_v L}{\pi D^4}.$$

The limit of capillary absorption is determined by the Kelvin-Helmholtz instability at the interface, which is confirmed by the analysis of the interaction between the vapor-liquid counter-current flows in a tube [6].

The critical length of the instability wave is

$$\lambda_{cr} = 2\pi\,(\sigma/\rho_{lv} g)^{0,5} < 1,$$

which amounts to approximately 1 cm for water or acetone at atmospheric pressure. Then

$$(2\pi/L)\,(\sigma\rho_{lv} g)^{0,5} < 1.$$

Inertia forces in open-type micro heat pipes can be commensurable with the gravity forces and capillary thrust. Therefore, hydrodynamic instability of the vapor-liquid flow can exist, which produces the phenomenon of capillary "flooding," i.e., the appearance of liquid crosspieces in the vapor channel.

Under certain conditions a situation arises, when the vapor channel of the micropipes is completely blocked by the liquid lock, and regions of "vapor-liquid" interface with various radii of the interface curvature appear along the pipe. In such a case, one can consider a successive connection of elementary heat pipes, the ends of which are liquid pump cups of different curvature.

If the fibrous structure of a moistened wood is analyzed, one can note that the space between the fibers (Fig. 1) has the form of a quadrangle with acute-angle fins filled the liquid-capillary arteries. In the gaps between the fibers, transfer of the liquid from the condensation region to the evaporation region occurs under the action of the pressure difference $P_v - P_l = \sigma/r(x)$. The liquid flow inside micro heat pipes is affected by the influence of the gravity field (hydrostatic pressure) and adhesion forces (interaction with the capillary walls, $P_{adh} = A/\delta^3$, where $\delta < 2\cdot 10^{-8}$ m is the distance in the direction of the wall, A is a constant depending on the properties of the solid body).

In the polycapillary structure of the wood or disperse material (zeolite), where there are macro- and micropores, one can observe the vapor motion through macropores in one direction and the liquid motion through

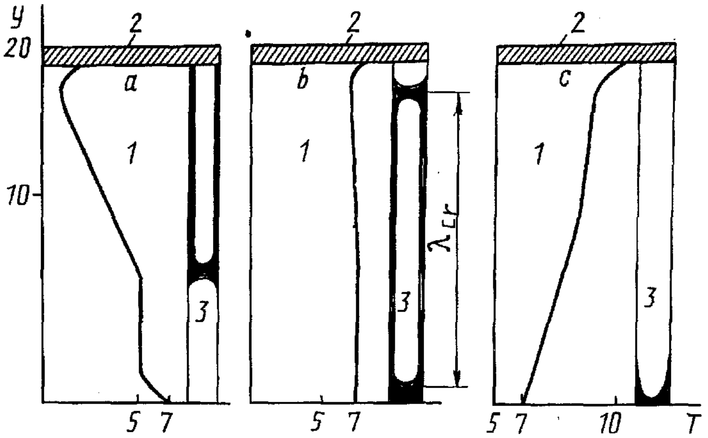


Fig. 2. Different variants of micro heat pipes with liquid evaporation from a capillary-porous body into the rarified gas flow in the wind tunnel: 1) glass (Plexiglas) particles d = 0.1-0.3 mm, wetted by water; 2) nickel metal-ceramic membrane, 3 mm thick, 70% porous, the dimensions of the pores are 5-15 $\mu$m; 3) vapor channel of a micro heat pipe inside a porous body formed at different densities of heat supply and pressure drops between the saturated vapor pressure in the porous body and vacuum chamber. y, mm; T, °C.

capillaries in the opposite direction under the effect of the temperature gradient and the moisture content. This motion occurs due to the pressure drop, caused by different curvatures of the meniscus of the "liquid-vapor" interface. In such a system the process of evaporation and condensation can occur in microcapillaries, which is accompanied by a significant enhancement of heat transfer due to a very thin liquid film of the order of microns.

The process of condensation heat transfer of vapor in micro channels of a rectangular or triangular type has been considered in work [7]. It was shown that the rate of condensation heat transfer of acetone at atmospheric pressure is $(50\text{-}60)\cdot 10^3$ W/(m$^2\cdot$°C), which exceeds by 10 times the heat transfer coefficient in condensation of acetone on a smooth surface.

Thus, open-type micro heat pipes do not possess an essential disadvantage of hermetic micro heat pipes - deterioration of heat transfer conditions in the condenser due to a thick condensate film.

For open-type micro heat pipes in which the transfer process occurs in accordance with the laws governing a continuous medium (Kn < 1), let us make use of the equations characteristic for the description of the given process in closed micro pipes in constructing a model of a stationary performance regime:

balance equations of momentum and energy conservation (Cotter, 1984)

$$\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial Y^2}\right)=\frac{dP}{dz} \tag{1}$$

$$\frac{8\pi V_v m_v}{K_v' A_v^2}=\frac{8\pi V_l m_l}{K_l' A_l^2}-\left(\frac{d}{dz}\right)\left(\frac{\sigma}{r_m}\right),$$
$$q_{\max}=\left(\frac{0{,}16\beta(K_l' K_v')^{0,5}}{8\pi H(L)}\right)\left(\frac{\sigma h_{fg}}{V_l}\right)\left(\frac{V_l}{V_v}\right)\left(\frac{A^{0,75}}{L_p}\right); \tag{2}$$

capillary pressure

$$\Delta P_c \geqslant \Delta P_+ + \Delta P_{\parallel} + \Delta P_l + \Delta P_v, \tag{3}$$

$R_c/r_h \geq 1$ (Peterson, 1988 [8]).

Radial heat transfer in micro heat pipes is described in the form [5]

$$T_i = T_s(P_{vi})\left[1+\frac{1}{h_{fg}\rho_l}\left(\sigma K+\frac{A}{\delta_l^3}\right)+\frac{2-f\,(2\pi R T_s)^{0,5}}{h_{fg}}\nu_{vi}\right].$$

Open-type micro heat pipes can be of the following kinds:

1. A condenser is connected with the volume occupied by a noncondensing gas, or it is connected with the environment through the capillary channel. The vapor pressure inside the micro heat pipe depends weakly on the thermal load $P_V = \text{const}$ (Fig. 2a).

2. The micro heat pipe is connected with the environment through a capillary lock (a porous membrane), and the liquid flow rate through it depends on the hydraulic resistance of the capillary lock and the thermal load. The micro heat pipe evaporator is coupled with the liquid accumulator (Fig. 2b).

To consider transient processes in such devices, one should make use of unsteady-state heat transfer models describing the kinetics and the dynamics of the molecular flow in phase transitions at the "liquid-vapor" interface. This approach to the description of the kinetics of the process is valid also for Kn > 1.

Considering that the number of molecules condensing on the liquid surface is equal to the quantity of molecules arriving at the surface, with mean velocity u of their thermal motion along the capillary, we obtain the equation

$$J = \left[\frac{M}{(2\pi RT)}\right]^{0,5} \cdot (P_s - P_v); \tag{4}$$

for a viscous flow regime

$$J_M = 1/4nmu = \frac{r^2\rho}{8\eta}\,\frac{(P_s - P_v)}{L}; \tag{5}$$

for a molecular-viscous flow regime

$$J_M = 1/4nmu = \frac{r^2\rho dP}{8\eta dy} + \rho K_c \frac{dt}{dy}; \tag{6}$$

and for a molecular flow regime

$$J_M = 1/4nmu = \frac{8}{3}\,\frac{M}{2\pi RT}\, r\,\frac{dP}{dy}. \tag{7}$$

If we denote the concentration of molecules at the liquid meniscus surface by c = mn, then

$$c = \frac{J_M}{1/4u} = \frac{r^2\rho dP}{2\eta u dy} + \frac{\rho K_c dt}{u dy}. \tag{8}$$

In the presence of a noncondensing gas in the slit or the capillary, the process of vapor transfer will depend on both the rate of vaporization kinetics and the diffusion of vapor molecules and molecules of the noncondensing gas:

$$j = -D = -\frac{D}{\delta}(c_s - c_\infty) = -\beta(c_s - c_\infty), \tag{9}$$

where $\beta$ is the mass transfer coefficient.

From Eqs. (4)-(8) and (9), it follows that

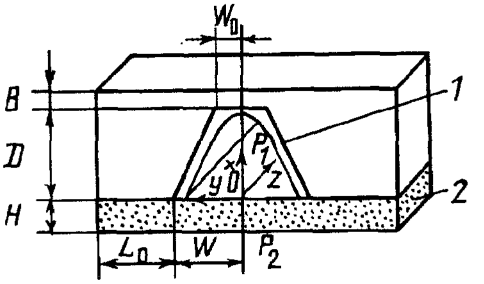
$$c_s = \frac{\beta}{1/4\,\mathrm{Au} + \beta}\, c_\infty; \tag{10}$$

$$j_M = \frac{1}{1/\beta + \dfrac{1}{1/4\,\mathrm{Au}}}\, c_\infty = K^* c_\infty, \tag{11}$$

where $K^*$ is a proportionality factor j and $c_\infty$ equal to

$$1/K^* = 1/\beta + 1/0{,}25\,\mathrm{Au}. \tag{12}$$

It follows from equation (12) that the total resistance $1/K^*$ equals the sum of the diffusion resistance $1/\beta$ and the kinetic resistance (1/0.25 Au). If the diffusion resistance is larger than the kinetic, then



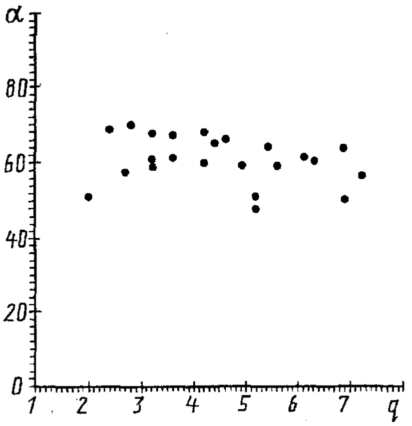


Fig. 3. Transverse condenser dimension of the micro heat pipe with a porous membrane-hydroseal: 1) condensate film on the microchannel wall surface; 2) porous membrane, through which the liquid film suction occurs; $W_0$, W, halfwidth of the top and the base of the microchannel; B, D, H, thickness of the condenser wall, microchannel height, thickness of the porous membrane; $L_0$, distance between microchannels.

Fig. 4. Dependence of the heat transfer coefficient on the heat flux density in the case of acetone vapor condensation in a micro heat pipe. $\alpha$, $10^3$ W(m$^2$·K); q, W/m$^2$.

$$c = \beta/0{,}25\,\mathrm{Au} \ll c_\infty,\quad 1/K^* = 1/\beta,\quad j = \beta c, \tag{13}$$

i.e., the evaporation rate is determined by the transfer rate (diffusion), since $\beta = D/\delta$ (D is the diffusion coefficient; $\delta$ is the boundary layer thickness). If the diffusion resistance is smaller than the kinetic: $1/\beta \ll 1/0.25$ Au, then $c = c_\infty$, $K^* = 0.25$ Au:

$$j_\mathrm{M} = 0{,}25\mathrm{Au}\,c_\infty, \tag{14}$$

i.e., the evaporation rate is determined by the rate of phase conversion of the liquid to the vapor.

Let us denote the diffusion Nusselt number by $\mathrm{Nu}_D$, and the Knudsen number by $\mathrm{Kn}_D$:

$$\mathrm{Nu}_D = \frac{\beta l}{D},\quad \mathrm{Kn} = \lambda/1, \tag{15}$$

where $l$ is a characteristic dimension (capillary diameter); $\lambda$ is the mean free path of vapor molecules. Taking into account that the diffusion coefficient is proportional to the product $u\lambda$: $D = \Gamma u\lambda$, where $\Gamma$ is a numerical coefficient ($\Gamma < 1$), we write

$$j_\mathrm{M} = K^*c = \frac{uc}{1/\Gamma\,\mathrm{Nu}_D\,\mathrm{Kn} + 1/0{,}25A} = \frac{\Gamma uc}{1/\mathrm{Nu}_D\,\mathrm{Kn} + 1/A} = \Gamma K^{**}uc, \tag{16}$$

where the total resistance $1/K^{**}$ is equal to

$$1/K^{**} = 1/\mathrm{Nu}_D\,\mathrm{Kn} + 1/A. \tag{17}$$

The diffusion resistance $1/\mathrm{Nu}_D\mathrm{Kn}$ is inversely proportional to the product of the Nusselt and Knudsen numbers ($\mathrm{Nu}_D\mathrm{Kn}$). In liquid evaporation in capillaries, the Knudsen number sharply increases ($\mathrm{Kn} \geq 1$); therefore the diffusion resistance becomes smaller than the kinetic in certain evaporation regimes, and the evaporation process is determined by the process of phase transition. When $P_s$ is larger than $P_v$, the vapor flow j is positive, and liquid evaporation in the heat pipe evaporator occurs; if the pressure difference is negative, vapor condensation occurs.

The mass flow rate of the evaporating liquid in the channel is proportional to the area of the "liquid-vapor" interface in every region of the heat pipe:

$$\Delta m_{ec} = j\Delta A_{ec} = jW_{ec}\Delta x, \tag{18}$$

where $\Delta A_{ec}$ is the area of the "liquid-vapor" interface in the evaporator or condenser, and $W_{ec}$ is the perimeter of that interface; $\Delta x$ is the length of the segment under consideration.

The above is of great practical importance for small-size heat pipes, in which a noncondensing gas can appear. In this case, the phenomenon found experimentally in work [8] is of interest, where it has been established that there was a two-way filling by a number of liquids in conical dead-end capillaries took place (which are anologs of slits with acute angles in micro heat pipes), accompanied by a sharp intensification of solution of the noncondensing gas (air) in the liquid.

Those experiments showed that filling of conical dead-end capillaries by liquids such as distilled water, ethyl alcohol, acetone not only occurs from the channel inlet, but also is accompanied by the formation and rise of the liquid column in the narrow dead-end section of the capillary. At the same time, up to the moment when the liquid fully occupies the capillary channel, which corresponds to the complete solution of the gas, the volumes formed by the liquid column penetrating from the inlet and by the column formed at the dead end of the capillary are comparable in an order of magnitude.

The experiments concerned with the mechanism of two-way filling have shown that the main contribution is made by the process of liquid recondensation from the meniscus of smaller curvature (A) to the meniscus of larger curvature (B).

As is known, the saturated vapor pressure over the concave liquid surface is lower than the saturated vapor pressure of the same liquid over the flat surface. Obviously, in our case, the directed diffusion vapor flow proceeds from the meniscus, formed at the inlet of the capillary channel, toward the narrow dead-end section of the capillary, where a thin sorption film having a very large curvature is present at the initial moment.

In the case of liquids such as water, ethyl alcohol, and acetone, an abnormally high rate of solution of a noncondensing gas in a conical capillary is observed. The effect discovered allows one to draw a conclusion about the nature of the interaction between the vapor molecule associations of those liquids and air molecules, resulting in an unusually high capture of the latter in the volume of the vapor gas space and their entrainment to the surface, at which condensation takes place.

Experimental verification of the existence of open-type micro heat pipes in porous moistened bodies is presented in [8] (Fig. 2). In evaporation of water into the flow of rarified (30 mm Hg) air heated up to 70°C from a porous structure in the form of 0.1-0.3 mm diameter glass or Plexiglas particles covered by a metal ceramic 3-mm-thick membrane, isothermal regions of superefficient thermal conductivity have been observed inside the porous structure. The geometric dimensions of these regions depended on both the characteristics of the porous structure (size of pores, permeability, thermal conductivity of particles) and external parameters of the gas flux (pressure, temperature, streamline flow velocity, the kind of gas, etc.).

A more detailed analysis of the hydrodynamics and heat transfer during vapor condensation in microchannels with porous membranes is presented in [7] (Fig. 3). It is shown in this work that heat transfer of condensation in the micro heat pipe region is very intense, since powerful capillary absorption of the condensate film by the porous structure is observed (Fig. 4).

In conclusion, attention should be drawn to new possibilities of realization of thermodynamic cycles in miniature open-type micro heat pipes, which makes it possible to maintain heat transfer enhancement in a number of technologies, such as drying and heat treatment of capillary-porous media, sorption and desorption in heat pumps and refrigerators, cooling and thermoregulation of apparatuses, computers, etc.

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