EFFECT OF PARAMETERS OF METAL FIBER CAPILLARY STRUCTURES ON MAXIMUM HEAT TRANSPORT BY HEAT PIPES

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The effect of the parameters of metal fiber capillary structures on the maximum heat transported by heat pipes is analyzed.

The results of analytic and experimental studies of the hydrodynamic restriction on the normal functioning of heat pipes (HP) with metal fiber capillary structures (MFCS), having constant average parameters over the percolation directions, are presented in [1, 2]. It is shown in particular that for fixed geometry of the HP housing, spread in the zone lengths, working temperature, and chosen heat carrier, the magnitude of the maximum transported heat flux Q_{max} can be controlled by changing the parameters of the structure.

In what follows, based on studies that we have completed, we analyze the effect of the parameters of MFCS on the magnitude of the maximum heat flow in order to ensure highest heat transport of developed HP.

Using the expressions obtained in [3] for the coefficient of fluid permeability and the available capillary pressure of the MFCS created, Eqs. (1) and (17) presented in [1] for the conditions $g \sin \varphi = 0$ and $g \sin \varphi > 0$ (heating zone above the condensation zone) can be written in the form

$$Q_{\max} = 2.19 N S_w \frac{F_{cs}}{L_e} \quad (g \sin \varphi = 0), \tag{1}$$

$$Q_{\max} = 2.19 N S_w \frac{F_{cs}}{L_*} \left(1 - \frac{\Delta p_{h1}}{\Delta p_{ac}}\right) \quad (g \sin \varphi > 0), \tag{2}$$

where

$$S_w = d_f \left[\frac{1-\Pi}{1+(1-\Pi)^2} - \frac{1+\ln(1-\Pi)}{2(1-\Pi)}\right] \frac{(1-\Pi)^3}{(1-\Pi_{lim})^{1,5}} \exp\left[-1.45 \frac{1-\Pi}{(1-\Pi_{lim})^{0,7}}\right].$$

The limiting porosity of MFCS is determined by the fiber diameter-to-length ratio d_f/l_f according to the relation $\Pi_{lim} = \exp(-6 d_f/l_f)$, obtained in [3].

The effect of the starting structural parameters of MFCS on Q_{max} for $g \sin \varphi = 0$ is described by a complex function S_w of three independent variables: Π, d_f, l_f (see Fig. 1, in which, as in Figs. 2 and 3, the dashed lines indicate the region of extrapolation of the function). The function S_w is related to the quantity S_d examined in [3] by the relation $S_w/S_d = \Pi$.

Analysis of the function S_w shows that in the entire range of structural parameters studied ($\Pi = 0.6$–0.95; $d_f = 0.02$–0.1 mm; $l_f/d_f = 40$–150) $\partial S_w/\partial d_f > 0$. For this reason for fixed Π and l_f the function S_w and the maximum heat flux Q_{max} increase with increasing fiber diameter. Investigation of the effect of porosity on S_w and the quantity Q_{max} shows that the function S_w has a maximum when the condition

$$\frac{1.45(1-\Pi)^2}{(1-\Pi_{lim})^{0,7}} \left[\frac{1-\Pi}{1+(1-\Pi)^2} - \frac{1+\ln(1-\Pi)}{2(1-\Pi)}\right] = \frac{2(1-\Pi)^2[2+(1-\Pi)^2]}{[1+(1-\Pi)^2]^2} - \frac{3+2\ln(1-\Pi)}{2}, \tag{3}$$

which causes the partial derivative $\partial S_w/\partial \Pi$ to vanish, is satisfied. Taking into account the dependence of Π_{lim} on d_f/l_f, condition (3) assumes the form

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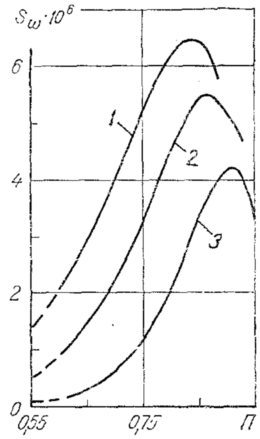

Fig. 1. Dependence of the quantity S_w (m) on the starting structural parameters: 1) $l_f/d_f = 43$; 2) 75; 3) 150.

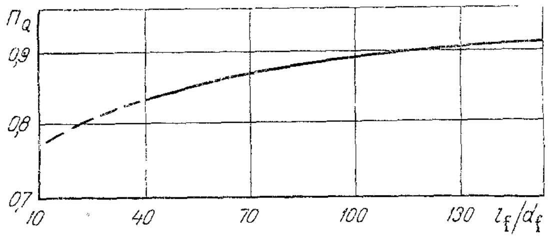

Fig. 2. Dependence of the optimal (from the point of view of attaining the highest value of Q_{max}) porosity on the ratio l_f/d_f for g. sin φ = 0.

$$\frac{d_f}{l_f} = -\frac{1}{6}\ln\left\{1-\left[\frac{1.45(1-\Pi)^2\left[\dfrac{1-\Pi}{1+(1-\Pi)^2}-\dfrac{1+\ln(1-\Pi)}{2(1-\Pi)}\right]}{\dfrac{2(1-\Pi)^2[2+(1-\Pi)^2]}{[1+(1-\Pi)^2]^2}-\dfrac{3+2\ln(1-\Pi)}{2}}\right]^{1,43}\right\}. \tag{4}$$

Equation (4) establishes the relation between the optimal (from the point of view of attaining the highest value Q_{max}) porosity $\Pi = \Pi_Q$ and the fixed ratio d_f/l_f. A graphical interpretation of (4), given in Fig. 2, permits easily determining the value of the porosity Π_Q for $g \sin\varphi = 0$. In the range of l_f/d_f studied, we have $\Pi_Q \approx 0.95\,\Pi_{lim}$.

For $g \sin\varphi > 0$, according to (2), the effect of the starting structural MFCS parameters on Q_{max} is manifested not only through the function S_w, but also the quantity $(1 - \Delta p_{h_1}/\Delta p_{ac})/L_*$, which is a complicated function of porosity and fiber dimensions (Δp_{h_1} and L_* are defined in [1]). For this reason, studying the nature and degree of influence of the structural parameters on Q_{max} for $g \sin\varphi > 0$ analytically is much more complicated than for $g \sin\varphi = 0$. It can be shown that in the entire range of the determining parameters

$$\frac{1-\dfrac{\Delta p_{h_1}}{\Delta p_{ac}}}{L_*} \approx \frac{1-\dfrac{\Delta p_h}{\Delta p_{ac}}}{L'_*}, \tag{5}$$

where $L'_* = L_e + 0.5s\Delta p_h/\Delta p_{ac}(L - L_h - 0.5L_c)$; s is a dimensionless quantity that describes the degree of uniformity of the MFCS [1].

As a result of mathematical analysis, including (5), of Q_{max} as a function of Π, the following condition is obtained for vanishing of the derivative $\partial Q_{max}/\partial\Pi$, for which Q_{max} has a maximum:

$$1.45\,\frac{1-\Pi}{(1-\Pi_{\lim})^{0.7}}-\frac{\dfrac{2(1-\Pi)^2\,[2+(1-\Pi)^2]}{[1+(1-\Pi)^2]^2}-\dfrac{3+2\ln(1-\Pi)}{2}}{(1-\Pi)\left[\dfrac{1-\Pi}{1+(1-\Pi)^2}-\dfrac{1+\ln(1-\Pi)}{2(1-\Pi)}\right]}=\varepsilon_p, \tag{6}$$

where

$$\varepsilon_p=\frac{1}{1-\dfrac{\Delta p_h}{\Delta p_{ac}}}-\frac{1-0.315\,\dfrac{\Delta p_h}{\Delta p_{ac}}\,[20.25\exp(-1.59s)+1]}{1+0.5s\,\dfrac{\Delta p_h}{\Delta p_{ac}}}.$$

The porosity $\Pi=\Pi_Q$, which satisfies Eq. (6), is optimum from the point of view of attaining the highest value of Q_{max} for $g\sin\varphi>0$. The solution of Eq. (6) for Π_Q is represented in Fig. 3 in the form of a graphical dependence $\Pi_Q=f(\varepsilon_p,\, l_f/d_f)$, which permits finding Π_Q by the method of successive approximations for fixed fiber dimensions, hydrostatic head, and heat carrier properties. The lower boundary of the porosity in Fig. 3 arises due to the corresponding boundary of the range in which the capillary transport properties of MFCS were studied. The upper limit is bounded by the limiting porosity. For $\Delta p_h=0$, which corresponds to the condition $g\sin\varphi=0$, we have $\varepsilon_p=0$, and condition (6) goes over into (3). Therefore, the function illustrated in Fig. 3 degenerates for $\varepsilon_p=0$ into the function Π_Q of l_f/d_f shown in Fig. 2.

Expressions (1) and (2), used as the basis for analyzing the effect of the structural parameters of MFCS on Q_{max}, were obtained with the pressure differential Δp_v in the HP vapor channel equal to zero. As a result of numerous calculations of Reynolds number Re and quantities Δp_v, performed within the scope of completed experimental investigations of low-temperature HP with MFCS, it has been established that in all cases the flow is laminar and the pressure differential in the vapor channel is negligible compared to the available capillary pressure. Including the quantity Δp_v in deriving the equation for Q_{max} showed that the effect of the hydrodynamics of the vapor on Q_{max} can become appreciable only for very small diameters of the vapor channel and some level of the ratio ν_v/ν_{fl}. But such parameter combinations are unlikely to occur in practice and often are simply unrealistic.

Therefore, the assumption $\Delta p_v=0$, used in deriving Eqs. (1) and (2), is completely justified. However, in order to investigate the effect of the thickness of the capillary structure δ_{cs} on Q_{max} in the entire range of variation of the thickness, including very small diameters of the vapor channel, it is necessary to analyze expressions whose derivation included the hydrodynamics of the vapor flow.

For $g\sin\varphi=0$, the pressure balance equation, including the quantities Δp_{ac}, Δp_{fl}, and Δp_v, is written as follows in expanded form:

$$\Delta p_{ac}=\frac{\nu_{fl}L_eQ_{max}}{rK_{cs}F_{cs}}+\frac{2\nu_vL_eU_v^2Q_{max}}{rF_v^3}. \tag{7}$$

For the conditions $g\sin\varphi>0$, using (5), we write:

$$\Delta p_{ac}-\Delta p_h=\frac{\nu_{fl}L'_*Q_{max}}{rK_{cs}F_{cs}}+\frac{2\nu_vL_eU_v^2Q_{max}}{rF_v^3}. \tag{8}$$

An analysis of expressions (7) and (8) as functions Q_{max} of δ_{cs} yields the following equations for determining MFCS thicknesses that ensure the greatest heat transport by HP:

for $g\sin\varphi=0$

$$F_{cs}=0.25\sqrt{2}\,F_v^2\sqrt{\frac{\nu_{fl}}{\nu_vK_{cs}(0.75U_v^2-\varepsilon_{sh}F_v)}}, \tag{9}$$

for $g\sin\varphi>0$

$$F_{cs}=0.25\sqrt{2}\,F_v^2\sqrt{\frac{\nu_{fl}}{\nu_vK_{cs}(0.75U_v^2-\varepsilon_{sh}F_v)}\,\frac{L'_*}{L_e}}, \tag{10}$$

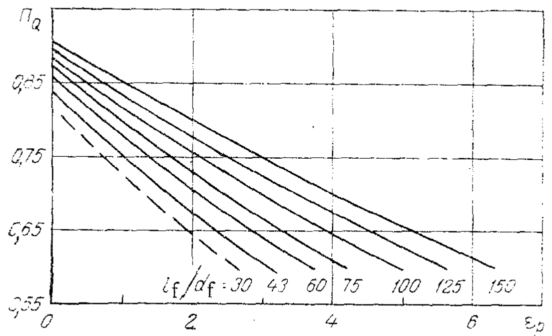

Fig. 3. The optimal (from the point of view of attaining the highest value of Q_{max}) porosity as a function of ε_p and l_f/d_f for g sin φ > 0.

where

$$F_{cs} = U_{in}\delta_{cs}\left(1-\frac{\delta_{cs}}{l}\right); \tag{11}$$

$$F_v = F_{in} - U_{in}\delta_{cs}\left(1-\frac{\delta_{cs}}{l}\right); \tag{12}$$

$$U_v = U_{in}\left(1-2\frac{\delta_{cs}}{l}\right); \tag{13}$$

l is the characteristic size of the transverse cross section, bounded by the inner parameter of the HP casing. For HP with circular and rectangular transverse cross sections $l = d_{in}$ and $l = 0.5\,(a + h)$. The quantity $\varepsilon_{sh} = U_{in}/l$ is the shape parameter of the transverse cross section of the pipe (for a circular section $\varepsilon_{sh} = \pi$; for a rectangular section $\varepsilon_{sh} = 4$).

The MFCS thickness that yields the highest value of Q_{max} is determined by the method of successive approximations according to (9) and (10) using (11)-(13).

Calculations using Eqs. (9) and (10) show that in many cases for some combinations of the determining parameters extremely large thicknesses (attaining 10 mm and more) are obtained for the structures. Such thicknesses greatly degrade the conditions for heat transfer and can lead to breakdown of the normal functioning of the HP with heat fluxes much less than Q_{max}. In addition, the technology for making HP with such structures is much more complicated. Therefore, an upper bound must be imposed on the thickness of the structures calculated using Eqs. (9) or (10). Based on experience in designing and investigating HP with MFCS, this restriction corresponds to a thickness of about 3-4 mm.

Thus, expressions and recommendations have been obtained for determining the optimal characteristics of metal fiber capillary structures for various orientations in a gravitational field, which yield the highest heat transport capacity of a heat pipe with fixed structural parameters of the casing, working temperature, and heat carrier.

NOTATION

Π, porosity of the capillary structure; Π_{lim}, maximum porosity; d_f, fiber diameter; l_f, fiber length; K_{cs}, coefficient of fluid permeability of the capillary structure; Δp_{ac}, available capillary pressure; δ_{cs} and F_{cs}, thickness and area of the transverse cross section of the capillary structure; d_{in}, inner diameter of the HP casing; a and h, inner dimensions of the rectangular transverse cross section of the HP casing; U_{in}, F_{in}, perimeter and area of the transverse cross section of the channel of the HP casing; U_v and F_v, perimeter and area of the transverse cross section of vapor channel; L, length of the HP; L_h, L_t, and L_c, length of the heating, transport, and condensation zones; $L_e = 0.5\cdot(L_h + L_c) + L_t$, equivalent percolation path length for g sin φ = 0; L_*, equivalent percolation path length for g sin φ 0; h_1, angle between the longitudinal axis of the HP and the horizontal plane; g, acceleration of gravity; Δp_h, Δp_{h_1} hydrostatic heads with and without the excess heat carrier, formed by partial drying of the structure; Δp_{fl}, viscous pressure losses in the fluid; $N = \sigma r/\nu_{fl}$, characteristic parameter of the heat carrier; σ, coefficient of surface tension of the fluid; r is the latent heat of vaporization; ν_{fl} and ν_v, kinematic coefficients of viscosity of the fluid and of the vapor on the saturation curve.

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NONSTATIONARY DOPPLER EFFECT FOR WAVES PROPAGATING IN NONHOMOGENEOUS MEDIA

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The theory of the frequency shift of continuous waves propagating in a medium whose properties depend on the coordinates and time is presented.

The fundamentals of the nonstationary frequency shift theory for waves propagating in a homogeneous medium whose properties vary in time are presented in [1-3]; the merits of the measurement and inspection methods based on this effect are demonstrated. In the general case, the medium under investigation can be nonhomogeneous, i.e., the wave propagation velocity in this medium not only can vary in time as a certain process develops, but it may also depend on the coordinates. A multilayer system provides a typical example.

If one assumes that the wave propagation velocity in the medium depends on all of the space coordinates and the time, i.e., $v = v(x, y, z; \tau)$, consideration of the frequency shift problem is made very difficult by the accompanying phenomena of phase surface distortion, interference, and diffraction. Therefore, we shall introduce certain simplifications which will make it possible to separate the above effect in "pure form." Consider the unidimensional case of propagation of a plane wave along the x axis in a medium whose properties depend only on the single coordinate x and the time τ, i.e., $v = v(x, \tau)$. Moreover, we neglect wave reverberations between the different layers of the medium.

The essence of the method used in [1-3] for determining the frequency shift consists in utilizing the law of motion of the phase surface of waves with a certain phase φ in the medium. The integral relationships given in these papers account for the change in the wave propagation velocity as the wave passes through the investigated section of the medium. It can readily be shown that they can be derived by solving the differential equation

$$\frac{dx}{d\tau} = v(\tau), \tag{1}$$

where $v(\tau)$ is the time dependence of the wave velocity in the medium. Actually, the general solution of Eq. (1) has the following form:

$$x(\tau) = \int v(\tau)\, d\tau + C = S(\tau) + C, \tag{2}$$

where $S(\tau)$ is the primitive function of $v(\tau)$, and C is the integration constant. If a wave with the phase φ is located at the point x_1 at the instant of time τ_1 (i.e., if it has entered the section of the medium under investigation), we have $x_1 = S(\tau_1) + C$, whence $C = x_1 - S(\tau_1)$, and we thus obtain the particular solution of Eq. (1),

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