LAWS OF FORMATION OF A PLUG OF LIQUID HEAT-TRANSFER AGENT IN THE VAPOR CHANNEL OF A THERMAL DIODE HEAT PIPE

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The authors present results of a theoretical and experimental study of the formation of a "plug" of liquid heat-transfer agent in the horizontal cylindrical channel of a thermal diode heat pipe in a gravity field.

An excess of liquid heat-transfer agent in the vapor channel of a heat pipe, due, for example, to a change of the operating temperature level, or during charging, considerably increases the thermal resistance of the pipe, and considerably affects the motion of the vapor and the liquid, causing a change of the thermal transfer capability [1-3]. However, the excess of liquid can also have a positive effect. Being in the vapor channel of a thermal diode heat pipe, designed to control the temperature of objects exposed to external conditions of variable sign, and blocking the evaporation zone, the liquid promotes efficient reverse operation (diode regime) of these heat pipes [3-5].

The authors know of a limited number of studies [2, 5] on investigating the influence of excess liquid on the characteristics of a heat pipe and analysis of conditions for formation of a liquid plug in the vapor channel. In addition, the conditions examined for filling of vapor spaces and arteries in the investigations of [2] are special, since they were obtained only from analysis of the operation of arterial heat pipes. The literature has no information on the laws of the process of liquid blocking of the vapor channels of thermal diode heat pipes in the reverse operating regime.

The object of this investigation is to determine the start of blocking by liquid of the cylindrical horizontal vapor channel of a thermal diode heat pipe in a gravity field in the reverse operating regime.

It has been established by the studies of [5] that in a horizontal location the process of blocking of a vapor channel by liquid in the reverse regime proceeds as follows (Fig. 1a). During supply of heat flux to the condensation and tank zones the heat-transfer agent evaporated is condensed first in the adiabatic zone (the transport zone) and then in the evaporation zone. Because of the special structural features of the thermal diode heat pipe (there is a discontinuity of the capillary structure at the junction of the condensation and tank zones) part of the heat-transfer agent, which is mainly being evaporated from the tank, remains in the heat pipe vapor channel. Over the period $0 < \tau < \tau_{cr}$ there is a uniform increase of the level of the liquid heat-transfer agent in the vapor channel and a change of shape of its free surface under the influence of capillary and hydrostatic forces.

At a specific time $\tau = \tau_{cr}$ the shape of the free surface of the liquid heat-transfer agent in the vapor channel is such that subsequent condensation leads to the formation of a liquid plug blocking the section $L_{bl}(\tau)$. The liquid plug begins to form from the end of the thermal diode heat pipe, the front of which is concave towards the vapor space. The vapor channel of the evaporation zone (or of the transfer zone) has a blocked section and also a section free for heat transfer by condensation. The increase of the length $L_{bl}(\tau)$ depends both on the regime parameters and the thermophysical properties of the liquid heat-transfer agent, and on the vapor channel geometry.

After all the heat-transfer agent has been withdrawn from the tank zone there is established in the vapor channel an equilibrium shape of the liquid—vapor surface of the liquid plug of length L_{bl} and a layer of liquid of thickness δ. A change of the heat-transfer agent mass after this equilibrium is established leads only to a change of L_{bl} for a long enough vapor channel.

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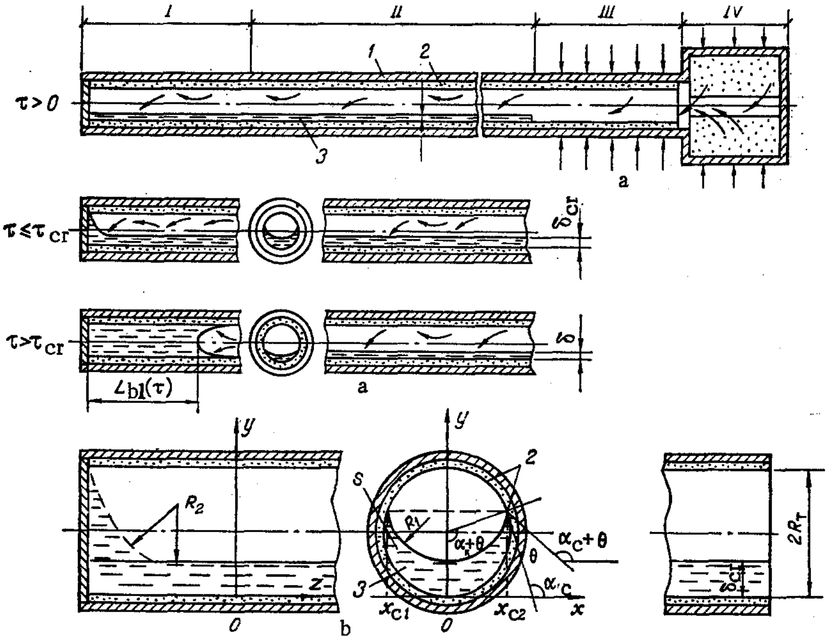

Fig. 1. Stages in blocking by liquid of a cylindrical vapor channel of a thermal diode heat pipe in the reverse regime (a), and a scheme for calculating the shape of the free surface at the moment the liquid plug forms (b): 1) wall of the heat pipe body; 2) capillary structure; 3) liquid heat-transfer agent; I-IV) respectively, the evaporation, transfer, condensation, and tank zones.

It follows from what was said above that in a cylindrical vapor channel the equilibrium shape of the liquid–vapor surface, both before and after formation of the plug, is determined by the ratio of the capillary pressure of the concave surface and the hydrodynamic pressure of the liquid. Therefore, to determine conditions for formation of the liquid plug in a gravity field we must solve the problem of finding the law for the variation of the shape of the free liquid surface whose pressure can overcome the hydrostatic pressure of a column of liquid of height $(2R_T - \delta_{cr})$.

We consider this problem under the following assumptions: 1) the motion of the vapor does not affect the process of liquid plug formation; 2) the liquid wets the surface of the vapor channel; 3) there is an equilibrium edge contact angle θ; 4) the mass of condensed liquid is in a quasiequilibrium state.

We shall first neglect also the influence of change of curvature of the shape of the liquid surface at the end of the heat pipe ($R_2 \to \infty$). Then the change of the shape of the surface will occur only in the plane xOy. The total potential energy F of the liquid in the channel is equal to the sum of the surface potential energy F_σ and the potential energy of the liquid mass F_g [6]:

$$F = F_\sigma + F_g = \int\limits_{x_{c1}}^{x_{c2}} \sigma\left\{\left[\left(\frac{dy}{dx}\right)^2 + 1\right]^{0.5} - \cos\theta\left[\left(\frac{df}{dx}\right)^2 + 1\right]^{0.5}\right\} dx + \int\limits_{x_{c1}}^{x_{c2}} [y^2(x)/2 - f^2(x)/2]\,\rho g dx. \quad (1)$$

The thermodynamic equilibrium upon wetting is the minimum total potential energy. We shall determine the minimum of this energy under the condition of constancy of the volume of liquid in the channel V = const, and, accounting for the assumption that the curvature varies only in the plane xOy, this converts to the form

$$V = SL_T = L_T \int\limits_{x_{c1}}^{x_{c2}} [y(x) - f(x)]\,dx = \text{const}, \quad (2)$$

and to conditions at the phase boundary (see Fig. 1b):

$$f(x_{ci}) = y(x_{ci}), \quad i = 1,\ 2. \quad (3)$$

Thus, the problem reduces to finding the conditional extremum (minimum) of the functional (1). It is known [6] that in this case the total variation of the functional $\delta F = 0$.

The application of variational methods to solution of the problem of minimizing the total potential energy F with conditions (2) and (3) gives a differential equation describing the shape of the free liquid surface:

$$\frac{\sigma \frac{d^2y}{dx^2}}{\left[1+\left(\frac{dy}{dx}\right)^2\right]^{2/3}} = \rho g y + C, \tag{4}$$

and the condition at the boundary points

$$\operatorname{arctg}\left(\frac{df}{dx}\right)\Big|_{x_{ci}} - \operatorname{arctg}\left(\frac{dy}{dx}\right)\Big|_{x_{ci}} = \theta, \quad i = 1, 2. \tag{5}$$

It is desirable to solve Eq. (4) in parametric form (the parameter is the slope angle of the tangent to the curve of the free surface α) and to determine the constant C at the point (0, δ). Taking this into account, and following transformations, the solution of Eq. (4) will have the form of Eqs. (6) and (7):

$$y(\alpha) = \delta + [(\sigma^2 + 2R_0^2\rho g\sigma(1-\cos\alpha))^{0,5} - \sigma]/\rho g R_0, \tag{6}$$

$$x(\alpha) = \int_0^{\alpha} \frac{R_0\sigma\cos t}{\sigma^2 + 2R_0^2\rho g\sigma\ (1-\cos t)]^{0,5}}\, dt, \tag{7}$$

where R_0 is the radius of curvature at the point (0, δ).

Having determined the boundary conditions (5) in the cylindrical channel

$$R_T \sin(\alpha_{ci} + \theta) = x(\alpha_{ci}),$$
$$R_T[1-\cos(\alpha_{ci} + \theta)] = y(\alpha_{ci}),\ i = 1.2, \tag{8}$$

and added to them the relation

$$K_{av1}\sigma = \rho g\,(2R_T - \delta_{cr}), \tag{9}$$

which describes the moment of equality of the capillary pressure of a concave surface and the hydrostatic pressure of the liquid layer $2R_T - \delta_{cr}$, we obtain the system (6)-(9) to determine the critical free surface, i.e., the conditions for forming the plug. The constant $K_{av1} = 1/\alpha_c \int_0^{\alpha_c} K_1(\alpha)d\alpha$ is the mean integral curvature of the surface at the critical equilibrium state. The critical equilibrium is one of the constants of equilibrium of the liquid in the channel at which an increase of surface curvature leads to the formation of a liquid plug.

Expanding the integrand expression K_{av1} with the aid of Eqs. (7) and (8), we determine the constant

$$K_{av1} = \frac{1}{\alpha_c}\int_0^{\alpha_c} \frac{[\sigma^2 + 2R_0^2\rho g\sigma(1-\cos\alpha)]^{0,5}}{\sigma R_0}\, d\alpha. \tag{10}$$

If we compare the radius R_2 with R_1 (e.g., a vapor channel closed by a solid wall, as in Fig. 1b), the problem of determining the condition for formation of a plug becomes three-dimensional and is difficult to solve. One approach to solving this problem is to assume that one of the main radii of curvature is constant. Then, using the approximation put forward in [3] and determining K_{av2} in the plane yOz in the form

$$K_{av2} = \left[\frac{\rho g}{2\sigma}\,(1-\sin\theta)\right]^{-0,5}, \tag{11}$$

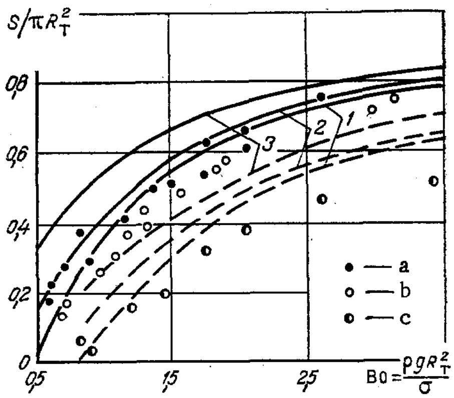

Fig. 2. Condition for forming a liquid plug of heat-transfer agent in the cylindrical horizontal vapor channels of heat pipes. Theory: solid lines are for open-end pipes ($R_2 \to \infty$) according to the system (6)-(9); the dashed lines are for a closed pipe end (K_{av2} from Eq. (11)) according to the system (6)-(8) and (12); 1-3) θ = 0, 15, and 50°. Experiment: a) water; b) acetone, in a channel with open ends; c) acetone in a channel with a closed end; θ = 0°.

we transform Eq. (9)

$$(K_{av1} + K_{av2})\,\sigma = \rho g\,(2R_T - \delta_{cr}). \tag{12}$$

Figure 2 shows the variation of the dimensionless area of cross section of the liquid $S/\pi R_T^2$ at the critical equilibrium state as a function of the geometrical parameters of the channel, the physical properties, and the wettability of the heat-transfer agent in the range typical of low-temperature heat pipes ($Bo = \rho g R_T^2/\sigma$ = 0.5-3). The solid curve $S/\pi R_T^2 = f(Bo)$ was obtained by solving the transcendental system (6)-(9), and the dashed curve was obtained from Eqs. (6)-(8) and (12) by Newton's numerical method, with a relative computational error of $1 \cdot 10^{-5}$.

The curve $S/\pi R_T^2 = f(Bo)$ divides the graph into two regions. In the region above this curve a liquid plug exists, and not below it. At the value $Bo \leqslant 0.5$ for $R_2 \to \infty$ and at $Bo \leqslant 0.8$ for K_{av2} determined from Eq. (11), a plug must form for any mass of heat-transfer agent. Analysis of the calculations shows a reduction of the ratio S/π_T^2 for improved wettability and in the presence of a closed channel, for large enough Bo.

The technique for experimental determination of the conditions for forming a liquid plug in a horizontal channel is as follows. Prior to the test the inner surface of the channel wall of the specimen was carefully cleaned with a chromic mixture and washed with the test liquid. Then the specimen was fastened rigidly in a horizontal position in a stand which was set up in a glass vacuum chamber. After evacuation of the chamber (drying of the specimen) it was filled with vapor of the test liquid. With the aid of a dropper whose needle passes through the end of the specimen the channel was slowly filled with test liquid until the plug formed. At the moment of formation of the liquid plug the mass m_{cr} was measured by weight and volume methods. The test results were correlated in the form $m_{cr}/(\pi R_T^2 \rho L_T) = f(Bo)$. The relative measurement error in m_{cr} did not exceed 15%. A comparison of the experimental data with theoretical calculations confirms the main relations of the theoretical analysis and good quantitative agreement is observed.

It has been established that the conditions for forming a liquid plug in open ($R_2 \to \infty$) and closed ($R_2 = 1/K_{av_2}$) cylindrical channels are determined from the laws for variation of the capillary pressure of a concave surface. Analysis of the results has shown that at a Bond number $Bo \leqslant 0.5$ for the open channel and $Bo \leqslant 0.8$ for the closed channel the plug forms for any excess liquid mass.

With the model developed for determining conditions for formation of the plug one can calculate the minimum mass of liquid heat-transfer agent necessary for creating a blocked zone in the reverse regime of a thermal diode heat pipe, and, therefore, one can estimate the geometrical parameters of the tank and the structural characteristics of its capillary structure.

NOTATION

R_1, R_2, principal radii of curvature of the free liquid surface; R_T, radius of the vapor channel; δ_{cr}, m_{cr}, layer thickness and liquid mass at the time of plug formation; L_{bl}, length of the blocked zone; S, area of liquid; τ, time; α_c, slope angle of the free liquid surface at the point of tangency with the capillary structure; Q, heat flux; x_{c_1}, x_{c_2}, abscissas of the point of contact of the free liquid surface y(x) with the surface of the capillary structure; θ, edge wetting angle; σ, surface tension; f(x), a function defining the shape of the inside surface of the channel capillary structure; ρ, liquid density; g, free-fall acceleration; L_T, length of the vapor channel of the specimen; K_{av}, average curvature of the liquid surface.

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