ANALYSIS OF THE TEMPERATURE FIELD IN THE CAPILLARY STRUCTURE OF AN "ANTIGRAVITY" HEAT PIPE

Yu. G. Fershtater and Yu. F. Maidanik UDC 536.248

The authors analyze the influence of the geometric parameters and the technical and physical properties of the capillary structure on the operating temperature of the "antigravity" heat pipe.

In antigravity heat pipes [1, 2] the capillary structure, located in the evaporation zone, fulfills the function of a capillary pump and a thermal gate [3, 4]. The latter becomes especially important when these heat pipes are oriented with positive slope angles, where transport of the heat-transfer agent in the liquid phase is accomplished in opposition to mass forces. In that case the thermal resistance of the heat pipe depends to a considerable extent on the temperature drop (or temperature head) arising when the heat load is supplied to the shut-off wall of the capillary structure which separates the peripheral system of vapor exit channels from the compensation cavity (Fig. 1). The corresponding pressure drop is related to the operating temperature of the vapor and the hydraulic resistance of the transport zone of the heat pipe by the following approximation:

$$\left.\frac{dP}{dT}\right|_{T_V} (T_V - T_{cc}) \simeq \Sigma\Delta P. \tag{1}$$

The quantity dP/dT is determined by the well-known Clapeyron–Clasius equation

$$\left.\frac{dP}{dT}\right|_{T_V} \approx \frac{L\rho_V}{T_V}. \tag{2}$$

Analysis of Eqs. (1) and (2) indicates that for $\Sigma\Delta P \approx$ const a change of the difference $T_V - T_{cc}$ leads to a corresponding change of the quantity dP/dT, which in turn depends on T_V. Therefore, we may choose the values of dP/dT and $T_V - T_{cc}$ so that the heat transfer in the heat pipe will be accomplished at a vapor temperature that is minimal for a given heat-transfer agent at the given external conditions. One way to realize this possibility is to vary the geometry or the thermophysical properties of the shut-off wall of the capillary structure. Below we analyze the efficiency of doing this.

We shall make the following assumptions: 1) the motion of the liquid in the capillary structure is laminar; 2) the liquid and the heat in the shut-off wall of the capillary structure are propagated only in the radial direction; 3) the temperatures of the liquid and the capillary structure skeleton are equal.

Allowing for this, the energy transfer equation in the shut-off wall of the capillary structure, in a cylindrical coordinate system, can be written as follows [5]:

$$\frac{\partial^2 T}{\partial R^2} + \frac{1}{R}(1-\varepsilon)\frac{\partial T}{\partial R} = 0, \tag{3}$$

where

$$\varepsilon = \frac{Qc_p}{2\pi Ll\lambda_e}. \tag{3a}$$

The boundary conditions are:

$$R = R_1 \quad T = T_1, \tag{4}$$

$$\lambda_e \left.\frac{\partial T}{\partial R}\right|_{R_1} = \frac{Qc_p}{2\pi LlR_1}(T_1 - T_0). \tag{5}$$

Physics and Technology Energy Studies Section, Ural Science Center, Academy of Sciences of the USSR, Sverdlovsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 51, No. 2, pp. 203-207, August, 1986. Original article submitted April 29, 1985.

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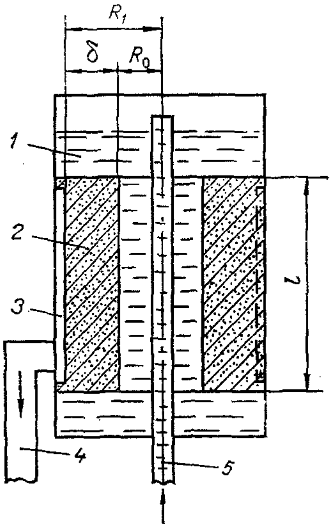

Fig. 1. Evaporation chamber of an antigravity heat pipe: 1) compensation cavity; 2) shut-off wall of the capillary structure; 3) vapor exit channels; 4) vapor duct; 5) condensate duct.

The boundary condition (5) reflects the fact that all the heat flux arriving at the shut-off wall goes to heat the heat-transfer agent from temperature T_0 to T_1.

We introduce the dimensionless temperature and coordinate:

$$\theta(R) = \frac{T(R) - T_0}{T_1 - T_0}, \quad r = \frac{R}{R_1}.$$

Then the problem of Eqs. (3)-(5) is written as:

$$\frac{\partial^2\theta}{\partial r^2} + \frac{1}{r}(1-\varepsilon)\frac{\partial\theta}{\partial r} = 0, \tag{6}$$

$$r = 1 \ \theta = 1, \ \frac{\partial\theta}{\partial r} = \varepsilon. \tag{7}$$

The solution of Eq. (6) with boundary conditions (7) has the form

$$\theta(r) = r^{\varepsilon}. \tag{8}$$

For convenience of further examination, we introduce the following notation:

$$r_0 = \frac{R_0}{R_1}, \ \theta_0 = \theta(r_0),$$

$$A = \varepsilon\lambda_e = \frac{Qc_p}{2\pi Ll}.$$

We first analyze the behavior of θ_0 for a nonvariable R_1. Figure 2 shows the results of the appropriate calculations in graphical form. From the graphs it can be seen that the relation $\theta(r_0)$ is very significant. The result obtained is qualitatively trivial, but a numerical expression of this relationship is not evident. We shall consider this question in greater detail. From Eqs. (3a) and (8) it follows that

$$\frac{\partial^2\theta_0}{\partial r\partial\lambda_e} = -\frac{A}{\lambda_e^2} r_0^{A/\lambda_e - 1}\left(1 + \frac{A}{\lambda_e}\ln r_0\right).$$

It can be shown that the following relations hold:

$$\lim_{\lambda_e \to 0} \frac{\partial^2\theta_0}{\partial r\partial\lambda_e}\bigg|_{r_0 = \mathrm{const}} = 0, \tag{9a}$$

$$\lim_{\lambda_e \to \infty} \frac{\partial^2\theta_0}{\partial r\partial\lambda_e}\bigg|_{r_0 = \mathrm{const}} = 0. \tag{9b}$$

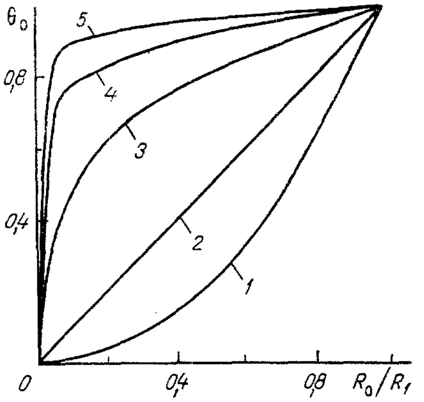

Fig. 2

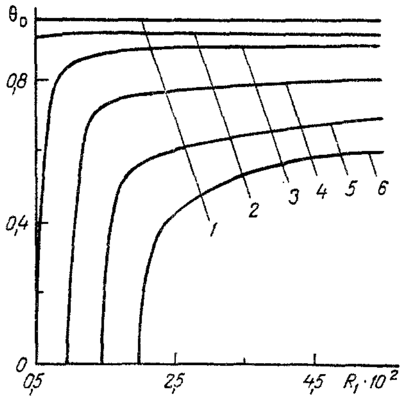

Fig. 3

Fig. 2. Temperature distribution of the inner surface of the capillary structure of an antigravity heat pipe (the heat-transfer agent is acetone, A = 1): 1) λ_e = 0.5 W/(m·deg); 2) 1; 3) 3; 4) 10; 5) 20.

Fig. 3. Temperature of the inner surface of the capillary structure as a function of its thickness and radius: 1) $\delta = 1\cdot10^{-3}$ m; 2) $3\cdot10^{-3}$; 3) $5\cdot10^{-3}$; 4) $1\cdot10^{-2}$; 5) $1.5\cdot10^{-2}$; 6) $2\cdot10^{-2}$ m. R_1, m.

It follows from Eqs. (9a) and (9b) that when $\lambda_e \to 0$, and also when $\lambda_e \to \infty$, the influence of r_0 on the temperature of the inner surface of the capillary structure decreases, and vanishes in the limit. For $\lambda_e = -A \ln r_0$ the dependence $\theta(r_0)$ is strongest . Qualitatively the dependences $\theta_0(\lambda_e)$is analogous, and vanishes in cases of perfect heat conduction and perfect insulation of the shut-off wall, and has a minimum for $\lambda_e = -A \ln r_0$. This result follows from analysis of the derivative $\partial^2\theta_0/\partial\lambda_e^2$. For example, for acetone heat pipes at characteristic heat loads of $(2\text{-}7)\cdot10^4$ W/m² the quantity λ_e, for which the dependence $\theta_0(\lambda_e)$ has a maximum, is 0.3-0.8 W/(m·deg). However, the effective heat conduction of actual capillary structures used in antigravity heat pipes is an order and more higher, and therefore a strong dependence of the working temperature on λ_e is not obtained [4].

Knowing these dependences we can solve, in the first approximation, the question of optimizing the capillary structure parameters. As was noted above, one can reach a given antigravity heat pipe working temperature by varying the geometric properties of the shut-off wall or of its heat conduction. The most general recommendation is this: we should vary the parameter with regard to which the working temperature is more conservative. We should estimate this by analyzing the ratio $(\partial^2\theta_0/\partial r\partial\lambda_e)/(\partial^2\theta_0/\partial\lambda_e^2)$: if it is less than 1 we will reach the given temperature better by varying the effective heat conduction of the capillary structure, and in the opposite case it is recommended to choose the optimal ratio R_0/R_1. The need for this kind of analysis can arise in the case when added limits are placed on the capillary structure parameters (hydraulic resistance, mass, material cost, availability, technology, etc.).

A further important facet of the analysis conducted is to explain the influence of the radius R_1 of the shut-off wall on the vapor temperature of an antigravity heat pipe. If δ is the wall thickness and $\delta = R_1 - R_0$, then $r_0 = (R_1 - \delta)/R_1 = 1 - \delta/R_1$. We rewrite Eq. (3a) as follows:

$$\frac{Qc_p}{2\pi Ll\lambda_e} = \frac{Qc_pR_1}{2\pi Ll\lambda_eR_1} = \frac{qc_pR_1}{L\lambda_e}.$$

Then Eq. (8) takes the form:

$$\theta_0 = (1-\delta/R_1)^{qc_pR_1/(L\lambda_e)},$$

$$\frac{\partial\theta_0}{\partial R_1} = (1-\delta/R_1)^{qc_pR_1/(L\lambda_e)}\ln(1-\delta/R_1)\times\frac{qc_p}{L\lambda_e} + \frac{qc_p\delta}{L\lambda_eR_1}(1-\delta/R_1)^{qc_pR_1/(L\lambda_e)-1}.$$

It can be shown that $\lim_{R_1\to\infty}\partial\theta_0/\partial R_1 = 0$. This means that, for a given value of δ, the dependence of the working temperature of the vapor in an antigravity heat pipe on the radius R_1 decreases as the latter increases. Here the power transmitted by the heat pipe increases, of course, other things being equal. Further, $\lim_{\delta/R_1 \to 0} \partial\theta_0/\partial R_1 = 0$ means that for an increased thickness of shut-off wall the influence of the radius R_1 on the temperature decreases. Both of these dependences are seen in Fig. 3. It follows from these results that it is quite permissible to increase the evaporator radius without a substantial increase in the capillary structure thickness, but a decrease leads to a need to increase the capillary structure thickness.

One should note the following: the temperature head at the shut-off wall is not equal to the difference of the vapor temperatures in the vapor-exit channels and the compensation cavity (the latter difference is larger). However, there is a strict relationship between the temperature of the outside surface of the shut-off wall and the vapor temperature in the vapor-exit channels on the one hand, and between the temperature of the inner surface of the shut-off wall and the compensation cavity on the other hand. Therefore, the behavior of the temperature head at the shut-off wall of the capillary structure as one parameter or another is changed allows one to estimate qualitatively how the vapor working temperature in an antigravity heat pipe would tend to change.

NOTATION

dP/dT, derivative determining the curvature of the saturation line; T_V, vapor working temperature; T_{CC}, mean temperature in the compensation cavity; $\Sigma\Delta P$, total pressure losses in the antigravity heat pipe circuit external to the evaporator; L, latent heat of vaporization; ρ_V, vapor density at the working temperature; R, ambient coordinate value; Q, heat flux transmitted by the heat pipe; c_p, specific heat of the liquid at constant pressure; l, length of the capillary structure; λ_e, effective thermal conductivity of the capillary structure; R_1, radius of the capillary structure; T_1, temperature at the point with coordinate R_1; T_0, temperature of the heat transfer agent at the inlet to the compensation cavity; δ, thickness of the capillary structure; R_0, inside radius of the capillary structure; q, heat flux density in the evaporation zone.

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