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MECHANISM FOR BOILING OF A LIQUID IN HEAT PIPE WICKS

Yu. K. Gontarev, Yu. V. Navruzov, V. F. Prisnyakov,
and V. N. Serebryanskii

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The authors describe a hypothesis that vapor-generating centers arise in the wicks of low-temperature heat pipes and a mechanism for activating these.

For liquid-metal heat pipes the processes of boiling of liquid in the wicks determine the region of crisis-free operation [1]. In the case of low-temperature heat pipes for which efficient operation has been confirmed experimentally, both in the evaporation regime and also with boiling of liquid in the porous structure, the boiling processes determine the region of most intense heat transfer [2, 3].

It is known [4, 5] that boiling in a porous structure begins at much lower values of specific heat flux than does boiling in a large volume. The only explanation for this is thought to be the hypothesis that there are sections within the porous layer with a ready phase interface to serve as boiling nuclei, a hypothesis first formed in [6] and then in [7, 8] and elsewhere. The existence of such nuclei for most types of porous structures used as the wicks of low-temperature heat pipes may be regarded as quite probable, especially for wicks described by a pore size distribution curve, and as experimentally proved [9] for mesh structures. However, the data of [6-13] on the number of these nuclei, their influence on the liquid boiling processes and the activation mechanism are not always physically well founded, have low reliability, and are in part contradictory. The result is that it is not possible to define specific heat flux regions corresponding to transition from the evaporation regime to the boiling regime in heat pipe wicks.

In this paper we describe a model of a mechanism for individual boiling of a vapor nucleus and computational relations based on it that allow one to determine the lower boundary of the region of transition from evaporation to boiling in low-temperature heat pipes. The upper boundary of this region, linked with a considerable increase of the heat-transfer intensity in developed boiling, can be determined from an equation from [14] giving a good description of the test data of [14].

In our opinion, the difference of the conditions for individual boiling of a liquid in the wicks of heat pipes and in a large volume has two causes: the existence of a solid body in the porous structure and the decrease of liquid pressure in the evaporation zone due to the action of capillary forces causing the liquid to move.

As the first cause, the complexity and spatial branching of the structure of the porous material produce local unwetted zones, particularly at places where elements of the body touch each other and regions with weak molecular bonding of the liquid and solid phases, and these are potential vapor generation centers. They are analogous to the nuclei [15] arising in a large volume of liquid on actual (roughened) heat-transfer surfaces in the hollows of roughnesses with impaired local wetting. The existence of such nuclei within the wick leads to a decrease of the liquid heating (and associated decreased specific heat flux) necessary to start boiling. The dimensions of these nuclei, according to [14], are close to those of the maximum pores of the given porous structure, but the liquid–vapor phase interface in it is formed at finer pores surrounding the nuclei. This is shown schematically in Fig. 1. Therefore, the vapor pressure at a nucleus, for not very small radii of curvature of the interface surface, when we can neglect its influence on P_{vn} [16], is larger than the pressure of the surrounding liquid by the amount of the capillary pressure arising in these

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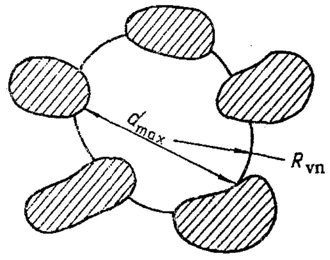

Fig. 1

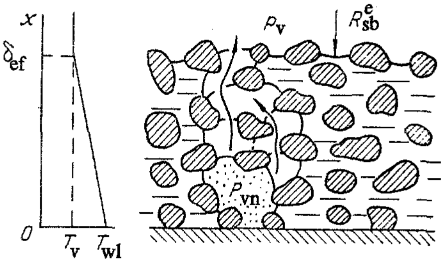

Fig. 2

Fig. 1. Scheme for a vapor nucleus.

Fig. 2. Increase of the vapor volume and sample distribution of temperature through the thickness of the wick at the moment of boiling.

fine pores:

$$P_{vn} = P_l + \frac{2\sigma}{R_{vn}}. \tag{1}$$

The decrease of liquid pressure leads to a situation where the conditions for boiling in the wick are eased in comparison with boiling in a large volume. In fact, if we denote by $2\sigma/R^e_{sb}$ the mean capillary pressure in the evaporation zone of a heat pipe transferring heat flux Q_{sb}, then the liquid and vapor pressures in the heat pipe heater zone may be linked by the relation

$$P_v = P_l + \frac{2\sigma}{R^e_{sb}}. \tag{2}$$

It follows from Eq. (2) that as P_v decreases the ratio between the first and second terms in Eq. (2) varies in favor of the latter, and this means that the effect of the influence of a decrease of P_l on the conditions of activation of a vapor nucleus in the wick will be more. Substituting Eq. (2) into Eq. (1), we obtain the condition for equilibrium of the liquid–vapor interface surface at a boiling nucleus located in the heat pipe wick:

$$P_{vn} - P_v = \frac{2\sigma}{R_{vn}} - \frac{2\sigma}{R^e_{sb}}. \tag{3}$$

The difference of the nucleus parameters from the equilibrium values converts Eq. (3) into an inequality. For example, upon the activation of a nucleus the left side of the equation becomes larger than the right, and when it collapses the sign of the inequality changes to the opposite.

For fixed values of P_v and R_{vn} the condition of equilibrium of Eq. (3), in contrast with the condition for equilibrium of the surface of a nucleus in a large volume [15], may be disrupted both due to an increase of P_{vn} (an increase of liquid heating) and due to an increase of $2\sigma/R^e_{sb}$ (an increase of the power transferred by the heat pipe). These two effects are interrelated in heat pipes. In the experiments of [17] a vibrating heat pipe was used to obtain a direct confirmation of the hypothesis that a decrease of liquid pressure influences the attainment of conditions of individual boiling in a wick. It was noted, in particular, that even small vibrations, and thus small fluctuations of liquid pressure linked to these, lead to a decrease of the specific heat flux for the onset of boiling from $0.9 \cdot 10^4$ to $0.8 \cdot 10^4$ W/m^2, and here the value $0.1 \cdot 10^4$ W/m^2 corresponds to 70 W of thermal power [17].

Figure 2 shows a scheme for growth of a vapor nucleus in a wick. Starting at a certain value of heat transfer, the nucleus increases in size (due to evaporation of liquid into it), expanding along the line of least resistance, i.e., preferentially along the larger pores. If the vapor permeability of the porous layer in the transverse direction is greater than in the longitudinal direction, then, starting at a certain time, the vapor volume leaves the wick surface. Visually we record here the moment of individual boiling. Depending on the ratio of pressure forces in the bubble, capillary pressure, and the liquid inertia forces, the vapor volume either collapses and the whole growth cycle repeats afresh, or a stable vapor-generating channel is formed whose hydraulic drag is determined by its diameter and crookedness.

Using the known thermodynamic transformations [15], from Eq. (3) we can obtain a relation for the heating of the wall liquid layers relative to the vapor temperature at the moment of boiling

$$\Delta T_{\mathrm{sb}} = \frac{2\sigma T_{\mathrm{v}}}{r\rho_{\mathrm{v}} R_{\mathrm{vn}}} - \frac{2\sigma T_{\mathrm{v}}}{r\rho_{\mathrm{v}} R_{\mathrm{sb}}}. \tag{4}$$

Assuming that heat is transferred by conduction to the evaporation surface at the moment immediately preceding activation of the nucleus, and also neglecting the influence of drying of the upper layers of the wick on its effective thickness, which is valid (since $Q_{\mathrm{sb}} \ll Q_{\mathrm{max}}$) for most regimes of boiling in low-temperature heat pipes, for the specific heat flux at the start of boiling we can write

$$q_{\mathrm{sb}} = \frac{\lambda_{\mathrm{ef}}}{\delta_{\mathrm{ef}}} \Delta T_{\mathrm{sb}} \xi. \tag{5}$$

Here the coefficient

$$\xi = \left(1 + \frac{R_{\mathrm{c}}}{\delta_{\mathrm{ef}}/\lambda_{\mathrm{ef}}}\right)^{-1} \tag{6}$$

takes into account the influence of the contact thermal resistance of the wick with the pipe wall. For low-temperature heat pipes the pressure losses over the vapor are negligibly small, and therefore we can assume that the heat flux transferred $Q_{\mathrm{sb}} = q_{\mathrm{sb}} F_{\mathrm{v}}$ and the capillary pressure $2\sigma/R^{\mathrm{e}}_{\mathrm{sb}}$ at the time of boiling may be linked by the following relation:

$$\frac{2\sigma}{R^{\mathrm{e}}_{\mathrm{sb}}} \simeq q_{\mathrm{sb}} \frac{\mu_l}{r\rho_l} \frac{F_{\mathrm{h}} l_{\mathrm{ef}}}{F_{\mathrm{w}} K_{\mathrm{w}}}. \tag{7}$$

Eliminating the quantity $2\sigma/R^{\mathrm{e}}_{\mathrm{sb}}$ from Eqs. (4), (5), and (7) and after some transformations we obtain the result that the specific heat flux for the start of individual boiling in heat pipe wicks is

$$q_{\mathrm{sb}} = \frac{2/R_{\mathrm{vn}}}{M^{-1}\delta_{\mathrm{ef}}/\xi\lambda_{\mathrm{ef}} + N^{-1}F_{\mathrm{h}} l_{\mathrm{ef}}/F_{\mathrm{w}} K_{\mathrm{w}}}, \tag{8}$$

where $M = \sigma T_{\mathrm{v}}/r\rho_{\mathrm{v}}$; $N = \sigma r\rho_l/\mu_l$.

In order to use Eq. (8) to calculate q_{sb} for low-temperature heat pipes, besides data on the geometric and thermophysical characteristics of the capillary structure and the working liquid, one must have information on the radius of curvature of the surface of the nuclei which act as vapor-generating centers. At present one cannot obtain any reliable data on the quantity R_{vn} in direct experiments. Therefore, the only (direct) method of determining R_{vn} is to develop a model of the boiling mechanism, to use it to obtain theoretical relations for $\Delta T_{\mathrm{sb}} = f(R_{\mathrm{vn}})$ and $q_{\mathrm{sb}} = f(R_{\mathrm{vn}})$, and to compare these with reliable experimental data on heating and the specific heat flux at the start of boiling. An analogous method of determining R_{vn} was adopted also in the analysis of the processes of boiling of liquids in a large volume [15].

Unfortunately, an attempt by the authors to use this method to obtain a theoretical relation for R_{vn} did not succeed, since the experimental data of [9, 14, 17-20] taken as reference points in calculations using Eq. (8) are unreliable, contradictory, and show differences of a factor of 2-3 for analogous structures. It is therefore natural that the quantity R_{vn} derived from these data has a scatter of (200-300)%, taking values from $20 \cdot 10^{-6}$ m to $60 \cdot 10^{-6}$ m for different wicks. Thus, without reliable experimental data on q_{sb}, which could be obtained on equipment operationally similar to that of [20], it is impossible to issue recommendations for correct determination of the radius of curvature of the surface of a boiling nucleus in heat pipe wicks.

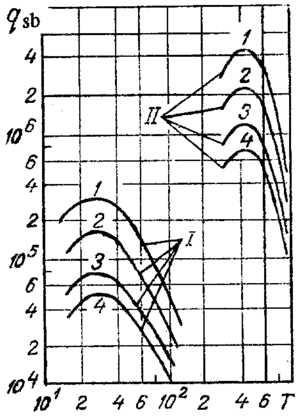

Fig. 3

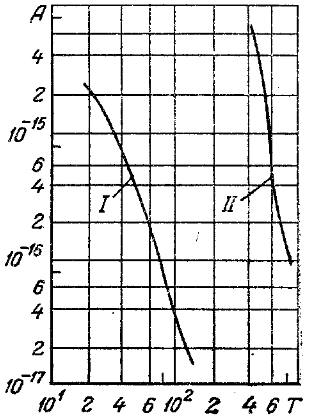

Fig. 4

Fig. 3. The specific heat flux for individual boiling q_{sb} (W/m^2) as a function of temperature T (°C) for water (I) and sodium (II): 1) $R_{vn} = 10 \cdot 10^{-6}$ m; 2) $20 \cdot 10^{-6}$; 3) $40 \cdot 10^{-6}$; 4) $60 \cdot 10^{-6}$ m.

Fig. 4. The quantity $(\varkappa^{-1}-1)\frac{\delta_{ef}F_wK_w}{\xi\lambda_{ef}F_h l_{ef}} \equiv (A)$ as a function of the temperature T (°C) for water (I) and sodium (II).

By way of example Fig. 3 gives values of the specific heat flux at the start of boiling, corresponding to the lower boundary of the transition region between evaporation and boiling for water and sodium heat pipes, calculated from Eq. (8) for the following values of the parameters: $\delta_{ef} = 1 \cdot 10^{-3}$ m, $\Pi = 80\%$, $F_h/F_w = 20$, $l_{ef}/K_w = 0.5 \cdot 10^{10}\ m^{-1}$. It can be seen that for boiling of sodium in a wick one needs heat flux densities one order higher than for water. This mainly stems from the fact that the groups M and N, made up from the thermophysical parameters, are appreciably larger for liquid-metal heat-transfer agents than for nonmetallic liquids. The values of M and N determine the influence of the working liquid on q_{sb} and can serve as criteria for choosing a suitable heat-transfer agent for given conditions.

It is easy to convert Eq. (8) to the following form:

$$q_{sb} = \frac{\lambda_{ef}}{\delta_{ef}}\xi\frac{2\sigma T_v}{r\rho_v R_{vn}}\varkappa, \tag{9}$$

by introducing the coefficient

$$\varkappa = \left(1 + \frac{M}{N}\xi\frac{\lambda_{ef}F_h l_{ef}}{\delta_{ef}F_w K_w}\right)^{-1}, \tag{10}$$

which governs the relation between the two causes of boiling in heat pipes: increased heating and drop of liquid pressure. Figure 4 shows the influence of the type of heat-transfer agent on the value of the coefficient $\varkappa$. It follows from Fig. 4 and analysis of Eq. (9) that the influence of the effects of a decrease of liquid pressure on the conditions of activation of a vapor nucleus increases with a decrease of temperature. This leads to the appearance of a maximum in the curve of temperature dependence of the specific heat flux at the start of individual boiling in the wick, in contrast with the monotonically falling dependence $q_{sb}(T)$ characteristic of boiling of a liquid in a large volume. It can be seen also that the coefficient $\varkappa$ depends to a considerable degree on the geometric and thermophysical characteristics of the wick.

NOTATION

Q, heat flux; q, heat flux density; T, temperature; P, pressure; σ, surface tension; ρ, density; λ, thermal conductivity; μ, dynamic viscosity; r, latent heat of evaporation; R, radius, thermal resistance; δ, thickness; l, length; F, area; K, permeability; Π, porosity; x, coordinate. Subscripts: l, liquid; v, vapor; e, evaporator; sb, start of boiling; vn, vapor nucleus; h, heater; w, wick; wl, wall; ef, effective; c, contact; max, maximum.

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