CALCULATION OF THE DENSITY OF ACTIVE NUCLEATION SITES IN THE BOILING OF LIQUIDS ON METAL-FIBROUS CAPILLARY-POROUS STRUCTURES

Yu. V. Fridrikhson, V. Yu. Kravets, and
M. G. Semena

The authors suggest a procedure for calculating the density of active nucleation sites in the boiling of liquids on porous coatings and a correlation for metal-fibrous structures.

The density of nucleation sites n exerts a substantial influence on the heat transfer rate in the boiling of liquids. The quantity n is a function of many parameters, namely, the density of the heat flux, pressure, surface roughness, its wetting, etc. In the case of the boiling of liquids on a porous coating it is necessary to additionally take into account the influence of geometric and thermophysical characteristics of the coating on the vaporization conditions. No calculation relations are practically known for determination of the density of active nucleation sites in the boiling of liquids on porous structures.

We consider, in a simplified form, the problem of the dimensions of active cavities [1]. It is known that upon attaining a superheating $\Delta T = 4\sigma T_s/(\rho_v r D_c)$ sufficient for the formation of a vapor bubble, the liquid may boil up in the cavity, whose mouth has the diameter D_c. We assume that upon attaining this superheating the liquid may boil up and the vapor phase may fill a pore with the diameter D_v. Such an approach has been adopted in [2] to determine the temperature of the onset of boiling on a porous surface. We plotted the dependences $D_v = f(\Delta T)$ for water that boils on a metal-fibrous capillary-porous structure (MFCPS) at the pressures $1 \cdot 10^5$ Pa and $0.1 \cdot 10^5$ Pa. These dependences are shown as hyperbolas 1 and 2 in Fig. 1. We assume that the thickness of the thermal boundary layer is equal to that of the capillary structure δ and the change in superheating over the height of the near-wall layer is linear (the family of straight lines 3 in Fig. 1). The hatched zones correspond to the segments of curves 4 and 5 of the differential function of pore size distribution (for the porosity $\Pi = 84$ and 40%, respectively) that include about 80% of all the pores of the structure. As is seen, for a coating with the porosity 84% the pores of the hatched zone are active even in the case of slight superheating ($\sim 1^{\circ}$C). For the coating porosity 40% and the same ΔT either boiling is absent or some very large pores are activated whose quantity is quite insignificant. With a further increase in the thermal load, the number of active pores no longer increases substantially on a surface with the coating porosity 84%, while on a low-porosity coating more and more new nucleation sites become activated and already at $\Delta T \approx 10^{\circ}$C almost all the pores with diameter near the maximum of curve 5 begin to act. Considerably higher superheatings are needed to activate the pores at a pressure $p = 0.1 \cdot 10^5$ Pa. Thus, it is evident that the density of the active vaporization sites n at a given surface superheating and the saturation pressure is strongly dependent on the porosity and the size distribution of the pores.

The number n may be determined from the relation

$$\frac{n}{n_\Sigma} = \int_{D_{\min}}^{D_{\max}} f(D)\, dD, \tag{1}$$

where $n_\Sigma = 4\Pi/\pi D_{ef}^2$ is the number of pores per unit area of the substrate; D_{ef}, $f(D)$ are the effective diameter of the pores and the differential function of pore size distribution, respectively [3]; $D_{\max,\min}$ are the maximum and minimum diameters of the active pores.
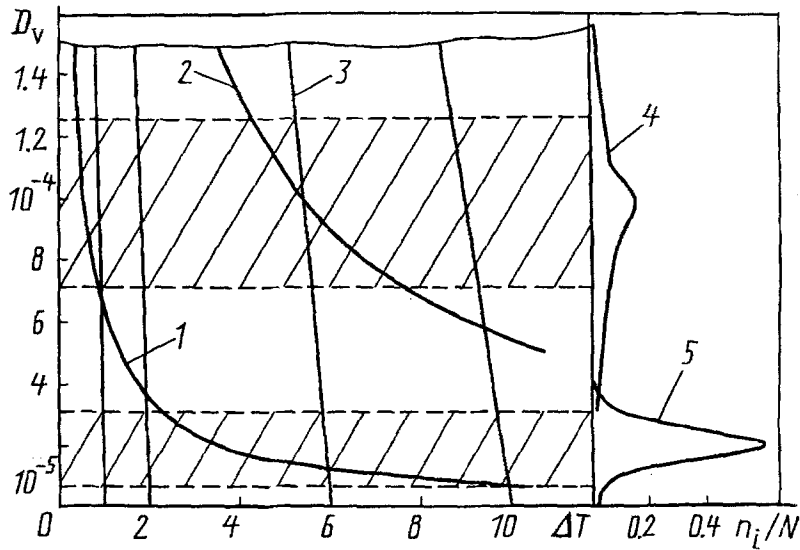

Fig. 1. Scheme of the solution of the problem of boiling-up of water in the pores of capillary structures ($\delta = 1$ mm): 1, 2) the dependences $D_v = f(\Delta T)$: 1) $P = 1 \cdot 10^5$; 2) $0.1 \cdot 10^5$ Pa; 3) change in the superheating of the liquid over the height of the near-wall layer; 4, 5) curves of the differential size distribution of the pores; 4) $\Pi = 84$; 5) 40%. D_v, m; ΔT, °C.
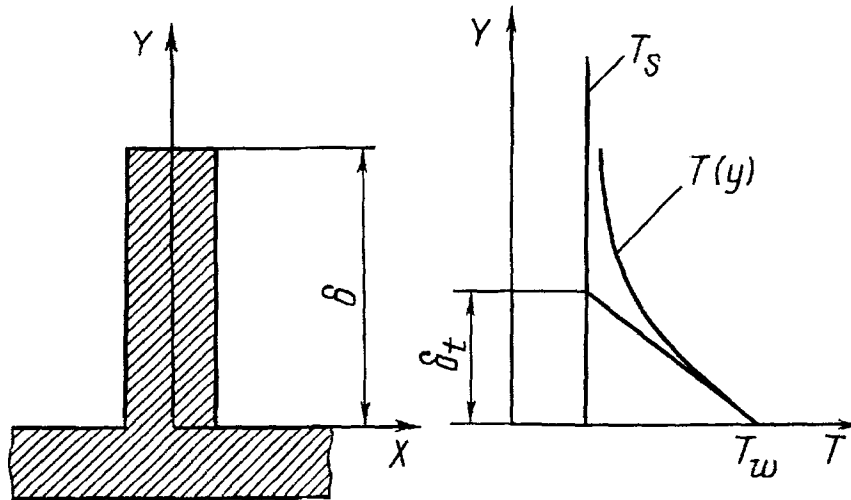

Fig. 2. Temperature distribution over the height of a conventional rib.

In accordance with [4]:

$$D_{\text{max, min}} = \frac{2}{3} \delta_t \left[1 \pm \sqrt{\left(1 - \frac{12 T_s \sigma}{(T_w - T_s) \delta_t r \rho_v} \right)} \right].$$

(2)

To calculate the thickness of the superheated boundary layer δ_t, we represent the porous structure conventionally as a system of interconnecting cylindrical capillaries with the diameter D_{ef}. In this case δ_t is determined as the distance from the heating surface (substrate) at which the tangent to the temperature profile of a conventional rib drawn through its base intersects the saturation temperature line of the liquid in the volume (Fig. 2). The density of the heat flux in the steam-generating channel q_{ch} may be calculated by the formula [5]

$$q_{\text{ch}} = \frac{2.7}{\delta} \left[\left(\sqrt{\left(\frac{1}{\Pi} - 1 \right)} \right) \lambda_{\text{liq}} \lambda_{\text{ch}} \right]^{0.5} (\Delta T - \Delta T^*),$$
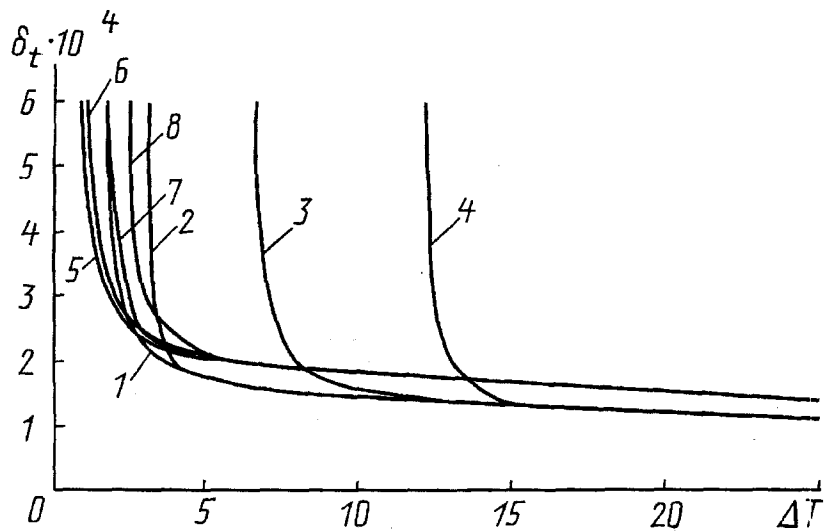
(3)

535

Fig. 3. Thickness of the superheated boundary layer versus superheating of the liquid in boiling on a porous coating ($\Pi = 60\%$, $\delta = 0.6$ mm, the coating material is copper): 1-4) water; 5-8) ethanol; 1, 5) $P = 1 \cdot 10^5$ Pa; 2, 6) $0.5 \cdot 10^5$; 3, 7) $0.2 \cdot 10^5$; 4, 8) $P = 0.1 \cdot 10^5$ Pa. δ_t, m.

where $\Delta T^* = 4\sigma T_s / r D_{ef} \rho_v$.

We now determine, in accordance with [5], the number of liquid channels m per vapor-removing channel and the number of nucleation sites M per unit area of heating:

$$m = 1.41 \cdot 10^{-3} \frac{\sigma r \rho_v \cos \Theta}{\mu_v q_{ch}} \left(\frac{d_f}{\delta} \right)^2 \left(\frac{\Pi}{1 - \Pi} \right)^3 - \Delta m, \tag{4}$$

$$M = \frac{n_\Sigma}{m + 1}. \tag{5}$$

The temperature field of a conventional rib may be calculated by the formula [6]

$$\Delta T_{con} = \Delta T \frac{ch\,(H\,(y - \delta))}{ch\,(H\delta)}, \tag{6}$$

here

$$H = \sqrt{\left(\frac{\overline{\alpha} U}{\lambda_{ef} f_r} \right)},$$

where $\overline{\alpha}$ is the mean local heat transfer coefficient in the vapor channel; U is the rib perimeter; λ_{ef} is the effective thermal conductivity [3]; f_r is the cross-sectional area of the rib.

We calculate the heat transfer coefficient $\overline{\alpha}$ by the formula for a slotted gap [7]:

$$\overline{\alpha} = \frac{\lambda_{liq}}{K \nu_{liq}} \left(\frac{\sigma\, q_{ch} \delta}{2 \rho_{liq} \rho_v\, D_{ef}^2\, r} \right)^{1/3}. \tag{7}$$

Assuming the number of ribs to be equal to the number of nucleation sites, we determine the rib cross section [8]:

$$f_r = \frac{1 - \Pi}{M}. \tag{8}$$

Having calculated, by formula (6), the temperatures in different cross sections over the height of a conventional rib, we may determine the thickness of the superheated boundary layer δ_t as a function of ΔT for each concrete capillary structure-liquid pair. For small superheatings ($\Delta T < \Delta T^*$) we assume $\delta_t = \delta$. Figure 3 shows the results of calculating δ_t for the boiling of water and ethanol on an MFCPS with the surface porosity 60% at different pressures. It is obvious that with an increase in ΔT the thickness of the superheated boundary layer decreases, so that the heat transfer in the interrib space increases and the cross-sectional area of a conventional rib decreases. The results of calculating δ_t agree well with experimental data of [9]. As ΔT increases, the effect of the pressure decreases and the thickness of the superheated boundary layer becomes self-similar relative to the pressure in the region of sufficiently large superheating. As is seen in Fig. 3, the self-similarity of δ_t relative to the saturation pressure in the boiling of ethyl alcohol sets in at a considerably smaller superheating than for water due to the decrease in ΔT^*. An increase in the porous structure thickness leads to an increase in δ_t. However, starting from some value of δ_b, the structure thickness no longer influences δ_t because of the high values of $\bar{\alpha}$ in the interrib space. The value of δ_b decreases with the MFCPS porosity.

Substituting δ_t into (2), we determine the maximum and minimum diameters of the active pores. To calculate the density of the active nucleation sites by formula (1), we employ the hypothesis [10] that the size distribution of the pores for an MFCPS is described by Gramme-Charles curves, which are a generalization of the normal and Poisson distributions. Then for the case $D_{max} > D_{ef} > D_{min}$

$$
\int_{D_{min}}^{D_{max}} f(D)\, dD = \Phi\left(\frac{D_{min} - D_{ef}}{\bar{\sigma}}\right) + \Phi\left(\frac{D_{max} - D_{ef}}{\bar{\sigma}}\right) +
$$
$$
+ \frac{A}{3!}\left[\varphi''\left(\frac{D_{min} - D_{ef}}{\bar{\sigma}}\right) - \varphi''\left(\frac{D_{max} - D_{ef}}{\bar{\sigma}}\right)\right] +
$$
$$
+ \frac{E}{4!}\left[\varphi^{(3)}\left(\frac{D_{max} - D_{ef}}{\bar{\sigma}}\right) - \varphi^{(3)}\left(\frac{D_{min} - D_{ef}}{\bar{\sigma}}\right)\right]. \tag{9}
$$

For $D_{max} > D_{min} > D_{ef}$

$$
\int_{D_{min}}^{D_{max}} f(D)\, dD = \Phi\left(\frac{D_{max} - D_{ef}}{\bar{\sigma}}\right) - \Phi\left(\frac{D_{min} - D_{ef}}{\bar{\sigma}}\right) +
$$
$$
+ \frac{A}{3!}\left[\varphi''\left(\frac{D_{min} - D_{ef}}{\bar{\sigma}}\right) - \varphi''\left(\frac{D_{max} - D_{ef}}{\bar{\sigma}}\right)\right] +
$$
$$
+ \frac{E}{4!}\left[\varphi^{(3)}\left(\frac{D_{max} - D_{ef}}{\bar{\sigma}}\right) - \varphi^{(3)}\left(\frac{D_{min} - D_{ef}}{\bar{\sigma}}\right)\right]; \tag{10}
$$

for $D_{ef} > D_{max} > D_{min}$

$$
\int_{D_{min}}^{D_{max}} f(D)\, dD = \Phi\left(\frac{D_{min} - D_{ef}}{\bar{\sigma}}\right) - \Phi\left(\frac{D_{max} - D_{ef}}{\bar{\sigma}}\right) +
$$
$$
+ \frac{A}{3!}\left[\varphi''\left(\frac{D_{min} - D_{ef}}{\bar{\sigma}}\right) - \varphi''\left(\frac{D_{max} - D_{ef}}{\bar{\sigma}}\right)\right] +
$$
$$
+ \frac{E}{4!}\left[\varphi^{(3)}\left(\frac{D_{max} - D_{ef}}{\bar{\sigma}}\right) - \varphi^{(3)}\left(\frac{D_{min} - D_{ef}}{\bar{\sigma}}\right)\right]. \tag{11}
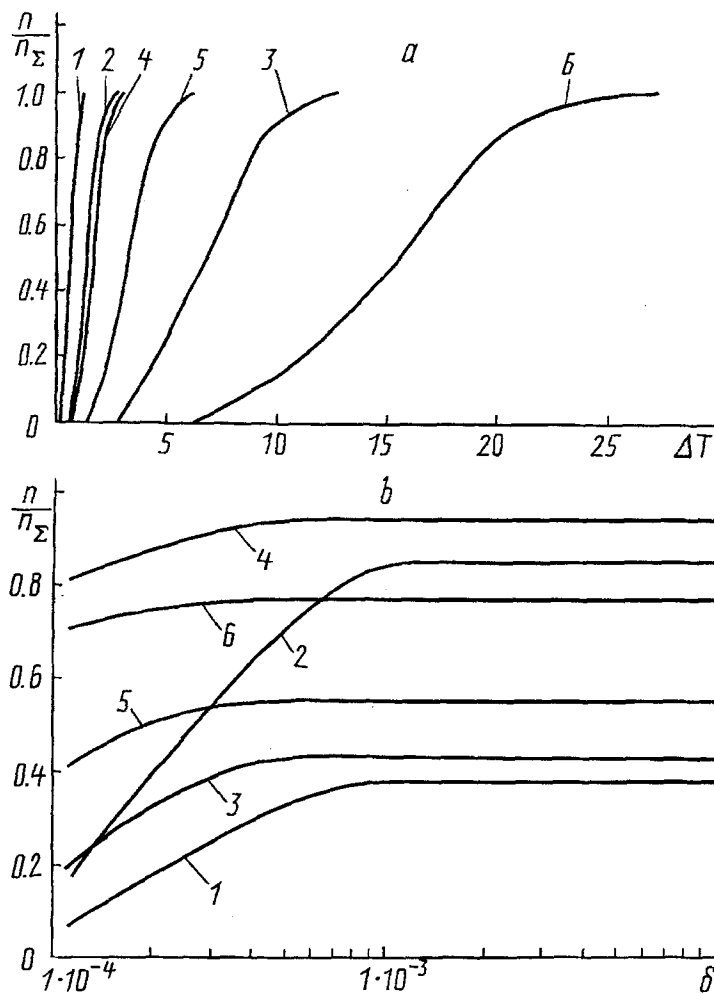$$

Fig. 4. Density of the active nucleation sites as a function of various parameters for the boiling of water on porous coatings (copper): (a) $n/n_\Sigma = f(\Delta T)$; $\delta = 1$ mm; 1-3) $\Pi = 84$, 4-6) 60%; 1, 4) $P = 1 \cdot 10^5$; 2, 5) $0.5 \cdot 10^5$; 2, 5) $0.5 \cdot 10^5$; 3, 6) $0.1 \cdot 10^5$ Pa; (b) $n/n_\Sigma = f(\delta)$, $P = 1 \cdot 10^5$ Pa; 1, 2) $\Pi = 84\%$; 1) $\Delta T = 0.7$; 2) 1°C; 3, 4) $\Pi = 60\%$: 3) $\Delta T = 2$; 4) 2.5°C; 5, 6) $\Pi = 40\%$: 5) $\Delta T = 4$; 6) 4.5°C. δ, m.

In formulas (9) — (11) the functions Φ, φ'', $\varphi^{(3)}$ are chosen from tables [11]. The asymmetry A, the kurtosis E, and the root-mean-square deviation $\bar\sigma$ for an MFCPS are calculated using the formulas [10]:

$$A = \exp\left[\left(\frac{l_f}{l_{f\,min}} \right)^{1.25} \frac{(1 - \Pi_{max})}{(1 - \Pi)^{0.7}} \right],$$

$$E = \exp\left[\left(\frac{l_{f\,min}}{l_f} \right)^{0.8} \Pi_{max} (1 - \Pi)^{0.7} \right],$$

$$\bar\sigma = 0.2 d_f^{0.7} l_f^{0.3} \Pi \left[\frac{0.28}{\sqrt{1 - \Pi}} + \Pi (\Pi^2 - 0.16) \right],$$

where l_f is the fiber length; $l_{f\,min} = 3 \cdot 10^{-3}$ m; d_f is the fiber diameter; Π_{max} is the maximum (limiting) porosity [3].

Using expressions (9) — (11) for an MFCPS with known structure parameters, we may determine the ratio n/n_Σ. Figure 4a shows the calculated dependence of n/n_Σ on ΔT for water at different pressures. The pressure

exerts a substantial influence on the superheating ΔT_{max} corresponding to the maximum number of active pores $(n/n_\Sigma = 1)$. Thus, for the boiling of water on a surface with the coating porosity 84% already at a small superheating $(\Delta T_{max} \approx 1.3^\circ C)$ practically all the pores are active at atmospheric pressure, while at $0.1 \cdot 10^5$ Pa $\Delta T_{max} \approx 12.5^\circ C$. A decrease in the porosity entails an increase in the effect of the pressure on n/n_Σ. The thickness of the porous structure exerts an influence on the number of active nucleation sites only in the region $\delta < \delta_b$. With a further increase in the thickness, the ratio n/n_Σ becomes self-similar relative to δ (Fig. 4b).

As a result of generalization we obtained the following relations for determining the number of active nucleation sites in the boiling of liquids on an MFCPS.

For $\delta \le \delta_b$ and $\Delta T \le \Delta T_b$

$$n = 8.5 \cdot 10^{-4} \Delta T^a \left(\frac{r\rho_v}{\sigma T_s} \right)^{4.2} \delta^{1.5} \left(\frac{1 - \Pi_{max}}{1 - \Pi} D_{ef} \right), \tag{12}$$

where $a = 1.65 \delta^{-0.15} \lambda_{ef}^{-0.08}$.

For $\delta > \delta_b$ and $\Delta T \le \Delta T_b$

$$n = 5.5 \cdot 10^{-7} \left(\frac{r\rho_v \Delta T}{\sigma T_s} \right)^{4.2} \left(\frac{1 - \Pi_{max}}{1 - \Pi} D_{ef} \right)^{1.42} \lambda_{ef}^b, \tag{13}$$

where $b = 2.05 \cdot 10^3 ((1 - \Pi_{max}) D_{ef}/ (1 - \Pi))^{0.83}$.

For $\Delta T > \Delta T_b$

$$n = 1.4 \left(\frac{r\rho_v \Delta T}{\sigma T_s} \right)^{1.55} \left(\frac{1 - \Pi_{max}}{1 - \Pi} D_{ef} \right)^{-0.07}. \tag{14}$$

Here

$$\delta_b = 9.27 \cdot 10^{-2} \left(\frac{1 - \Pi_{max}}{1 - \Pi} D_{ef} \right)^{0.47};$$

$$\Delta T_b = 246 \frac{\sigma T_s}{r\rho_v} \delta^{-0.15} \left(\frac{1 - \Pi_{max}}{1 - \Pi} D_{ef} \right)^{-0.44} \quad \text{for} \quad \delta \le \delta_b,$$

$$\Delta T_b = 282 \frac{\sigma T_s}{r\rho_v} \left(\frac{1 - \Pi_{max}}{1 - \Pi} D_{ef} \right)^{-0.53} \quad \text{for} \quad \delta > \delta_b.$$

Relations (12)–(14) generalize satisfactorily the results of calculation of the number of active nucleation sites in the boiling of water, ethanol, acetone, and DEF fluoroorganic liquid dielectric on an MFCPS. They relate directly the number of active pores to the superheating of the liquid, its thermophysical properties, and characteristics of the capillary structure. The obtained parameter n may be used in correlations for heat transfer in boiling on an MFCPS.

NOTATION

l, length; d, diameter; D, pore diameter; δ, thickness of the coating; n, density of the active nucleation sites; σ, surface tension of the liquid; θ, wetting angle; ρ, density; r, heat of vaporization; μ, dynamic coefficient of viscosity; ν, kinematic coefficient of viscosity; λ, thermal conductivity; q, heat flux density; P, pressure; T, temperature; ΔT, temperature drop. Subscripts: f, fiber; ef, effective; max, maximum; min, minimum; b, boundary; ch, channel; s, saturation; v, vapor; liq, liquid.

REFERENCES

1. V. I. Tolubinskii, Heat Transfer in Boiling [in Russian], Kiev (1980).
2. N. N. Savkin, A. S. Komendantov, Yu. A. Kuzma-Kichta, and M. N. Burdunin, Inzh.-Fiz. Zh., 58, No. 5, 808-813 (1990).
3. M. G. Semena, A. N. Gershuni, and V. K. Zaripov, Heat Pipes with a Metal-Fibrous Capillary Structure [in Russian], Kiev (1984).
4. C. Y. Han and P. Griffith, Int. J. Heat Mass Transfer, 8, No. 6, 887-904 (1965).
5. O. N. Man'kovskii, O. B. Ioffe, L. G. Fridgant, and A. R. Tolchinskii, Inzh.-Fiz. Zh., 30, No. 2, 310-316 (1976).
6. V. P. Isachenko, V. A. Osipova, and A. S. Sukomel, Heat Transfer [in Russian], Moscow (1975).
7. A. I. Leont'ev, B. M. Mironov, Kh. K. Kurbanov, and S. D. Korneev, Izv. VUZov, Mashinostr., No. 3, 85-87 (1977).
8. V. K. Orlov and V. N. Savel'ev, Teploénergetika, No. 8, 66-69 (1980).
9. G. N. Danilova and A. V. Tikhonov, Izv. VUZov, Priborostroenie, 30, No. 7, 88-92 (1976).
10. A. P. Nishchik and M. G. Semena, Inzh.-Fiz. Zh., 53, No. 2, 321-322 (1987).
11. A. K. Mitropol'skii, Methods of Statistical Calculations [in Russian], Moscow (1971).