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INITIAL SUPERHEATING OF A LIQUID IN BOILING ON A POROUS SURFACE

V. M. Polyaev, B. V. Kichatov, and
V. E. Lyubimov

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A new model of boiling of a liquid on porous surfaces is proposed based on which a dependence for the superheating of the liquid at the beginning of boiling is derived. The effect of regime and structural parameters on the initial superheating is analyzed. The results obtained are compared with experimental data.

In a number of branches of technology, the regimes of evaporator operation are characterized by extremely low temperature heads and accordingly low heat-flux densities [1]. This holds true for condensers-evaporators of air-fractionating units, evaporators used in the refrigeration industry, and others.

In evaporators that operate as components of refrigerating machines an increase in the temperature difference is associated with impairement of the indices of the refrigerating plant as a whole. For example, in cascade-type designs, a temperature decrease from 5–7 to 2–3°C decreases energy consumption for the same heat-exchange surface by 10–15% [2]. However, for these low temperature differences, the heat flux to the coolant is transferred under conditions of undeveloped boiling; therefore the coefficient of heat transfer to it often proves to be lower than its value from a "hot" heat-transfer agent. This leads to very large overall dimensions for heat-exchange apparatuses and to unsatisfactory weight characteristics for them.

The most efficient method of intensifying boiling heat transfer is to use porous surfaces. Therefore, the problem of determining the initial superheating of a liquid in boiling on porous surfaces is a pressing one, for example, when seeking to decrease the temperature difference and to have sufficiently intense heat transfer owing to boiling of a heat-transfer agent.

Numerous works are currently known concerned with this problem but, somehow or other, they are in agreement that when the superheating is calculated by the Clausius–Clapeyron formula Laplace's pressure difference between the liquid and vapor phases is taken as the pressure difference ΔP. Thus, in [3], the authors give a relation for the superheating of wall layers of a liquid with respect to the temperature of the vapor at the moment it starts to boil

$$\Delta T_{\text{s.b}} = \frac{2\sigma T_{\text{sat}}}{r\rho_{\text{vap}}} \left(\frac{1}{R_{\text{v.n}}} - \frac{1}{R_{\text{s.b}}} \right),$$

where $R_{\text{v.n}}$ is the radius of curvature of a vapor nucleus; $R_{\text{s.b}}$ is the average radius of curvature of the interface in a capillary structure; $\Delta T_{\text{s.b}} = T_{\text{s.b}} - T_{\text{sat}}$ is the temperature difference.

For smooth surfaces, the boiling point is governed by one characteristic size, namely, the radius of the throats of active cavities on the heated surface R_{act}. In the presence of porous surfaces, two characteristic sizes – R_{act} and the minimum radius of the pores occupied by the vapor as it "breaks down" the coatings R_{br} – are introduced in [4]. It is the smaller of them that governs the initial superheating, which corresponds to the arrival of the first vapor bubbles at the exterior surface of the coating:

$$\Delta T_{\text{s.b}} = \frac{2T_{\text{sat}}\,\sigma\cos\gamma}{r\rho_{\text{vap}}\,R},$$

N. E. Bauman Moscow State Technical University, Moscow, Russia. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 71, No. 1, pp. 173-175, January-February, 1998. Original article submitted November 25, 1996.

where γ is the wetting angle; $R = \min(R_{\mathrm{act}}, R_{\mathrm{br}})$.

It should be noted that, for any choice of the radius in Laplace's formula, it will determine the resistance to escape of vapor molecules from the surface of the liquid meniscus.

Below we consider boiling of a liquid on finely porous surfaces, i.e., ones where the hydraulic resistance of vapor escape exhibited by the porous structure is comparable with the resistance in bubble growth on the exterior surface.

In the event that the diameter of the bubbles at departure is larger than the characteristic pore size (this case corresponds to large pressures and heat loads), steady vapor zones that occasionally oscillate form in the porous matrix [5].

We replace the real porous structure by a perforated screen. The velocity of the outflow through an orifice is related to the velocity of the outflow through the narrowest cross section of the neck of the growing bubble ω^*_{vap} by the contraction coefficient

$$\omega_{\mathrm{vap}} = \varphi^2 \omega^*_{\mathrm{vap}} . \tag{1}$$

The maximum outflow velocity is determined by the pressure difference under whose action the vapor flows out into the bubble (accurate to the outflow coefficient):

$$\omega^*_{\mathrm{vap}} = \sqrt{\left(\frac{2\Delta P}{\rho_{\mathrm{vap}}}\right)} . \tag{2}$$

The mean mass velocity of bubbling of the vapor through the perforated screen is determined by the Kutateladze formula [6]

$$\frac{\omega_{\mathrm{vap}} \sqrt{\rho_{\mathrm{vap}}}}{\sqrt[4]{\sigma g (\rho_{\mathrm{vap}} - \rho_{\mathrm{liq}})}} = C \sqrt[12]{\left(\frac{\sigma}{g (\rho_{\mathrm{vap}} - \rho_{\mathrm{liq}}) R^2}\right)} , \tag{3}$$

where $C = \mathrm{const}$.

Thus, for the adopted scheme of boiling, the velocity of the outflowing vapor is constant, i.e., does not depend of the heat load (unlike a smooth surface where it is proportional to the applied heat load), and is governed by the physical properties of the liquid and the diameter of the pores.

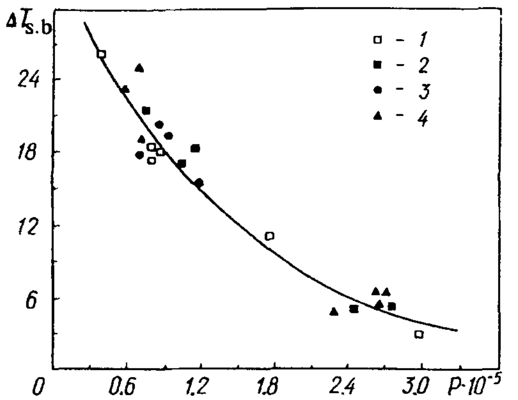
The vapor pressure above the perforated screen is higher than the pressure in the volume by the magnitude of the loss ΔP. Let us consider that the superheating of the liquid is determined by ΔP; then the Clausius–Clapeyron law yields

$$\Delta T_{\mathrm{s.b}} = \Delta P \frac{T_{\mathrm{sat}} (\rho_{\mathrm{vap}} - \rho_{\mathrm{liq}})}{r \rho_{\mathrm{vap}} \rho_{\mathrm{liq}}} . \tag{4}$$

Substituting (1)-(3) into (4), we obtain

$$\Delta T_{\mathrm{s.b}} = \frac{\sigma g (\rho_{\mathrm{vap}} - \rho_{\mathrm{liq}}) C^2}{2\varphi^2} \left(\frac{\sigma}{g (\rho_{\mathrm{vap}} - \rho_{\mathrm{liq}}) R^2}\right)^{1/6} \frac{T_{\mathrm{sat}} (\rho_{\mathrm{vap}} - \rho_{\mathrm{liq}})}{r \rho_{\mathrm{vap}} \rho_{\mathrm{liq}}} . \tag{5}$$

In setting up relation (4), in the Clausius–Clapeyron formula we take the hydraulic pressure difference of the vapor when it escapes from the porous structure into the volume. Substantiation of the adopted hypothesis can be provided by the fact that the average radius of the pores in the matrix is two orders of magnitude larger than the size of the active cavities on the smooth surface; however the superheating that corresponds to the start of boiling on a porous surface is an order of magnitude lower than on a smooth surface. In order words, superheating of the liquid is necessary for the molecules to overcome the hydraulic pressure exerted on the vapor by the porous structure, rather than Laplace's pressure difference on the surface of the liquid meniscus (the radius of the meniscus



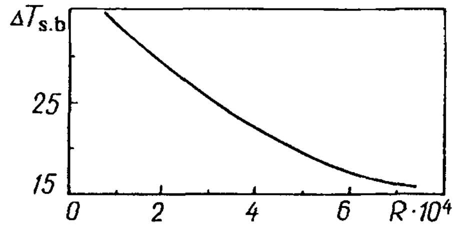


Fig. 1. $\Delta T_{s.b}$ vs. pressure P for surfaces with sprayed coatings (the heat-transfer agent is water): the curve is a calculation by formula (5); 1, 2) porosity $\varepsilon = 0.32-0.36$, coating thickness $h = 0.2$ and $h = 0.3$ mm; 3) $\varepsilon = 0.32-0.36$; $h = 0.5$ mm; 4) $\varepsilon = 0.28-0.32$; $h = 0.4$ mm [4]. $\Delta T_{s.b}$, K; P, Pa.

Fig. 2. $\Delta T_{s.b}$ vs. pore radius R (calculation by formula (5); water); $P = 0.031$ MPa, $T_{sat} = 343$ K, $\sigma = 64.47 \cdot 10^{-3}$ N/m, $\rho_{vap} = 1000$ kg/m^3, $\rho_{liq} = 0.198$ kg/m^3, $r = 2333.8$ kJ/kg, $\varphi = 0.7$, $C = 3.5$. R, m.

in boiling of a liquid on a porous structure is two orders of magnitude larger than the corresponding radius of the throats of the active cavities on a smooth surface).

We estimate the superheating $\Delta T_{s.b}$ obtained by formula (5) as compared to the experimental data of [7], in which the boiling of Freon-12 on steel tubes with a coating produced by sintering a metal powder was studied. According to [7]: $C = 3.5$; $\varphi = 0.7$; $\sigma = 11 \cdot 10$ N/m^3; $T_{sat} = 283$ K; $\rho_{vap} = 1362.7$ kg/m^3; $\rho_{liq} = 24.18$ kg/m^3; $r = 147.7$ kJ/kg; $R = 10^{-3}$ m. From (5) it follows that $\Delta T_{s.b} = 0.5^{\circ}$C, which is quite in agreement with the experimental data of [7].

The effect of the pressure and the pore radius on $\Delta T_{s.b}$ in boiling of water is presented in Figs. 1 and 2. It is evident that a pressure increase leads to a significant decrease in $\Delta T_{s.b}$, but a change in the pore radius has only a slight effect.

NOTATION

T, temperature; G, surface tension; P, pressure; r, latent heat of vaporization; R, pore radius; ρ, density; g, free-fall acceleration; w, velocity; φ, outflow coefficient. Subscripts: liq, liquid; vap, vapor; s.b, start of boiling; v.n, vapor nucleus; sat, saturation; act, active cavity; br, breaking down; *, neck of a bubble; min, minimum.

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