EFFECTS OF A POROUS COATING ON BOILING ONSET IN A TUBE

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A method is given for recording the onset of water boiling in a tube; a formula is given for the onset at a porous-coated surface, which applies for free or forced convection.

Very restricted data are available [1-3] on heat transfer on boiling under forced motion in a porous-coated channel, and hardly any measurements have been made on the characteristic for the start of boiling and there are no recommended formulas for the wall superheating $(T_w - T_s)_{bo}$, for which vapor formation starts in such channels.

We used two vertical working sections: a tube with porous coating and a technically smooth one. The parts were heated by passing alternating current through the tubes. The technically smooth one was of internal diameter 8 mm, wall thickness 0.5 mm, and length 1800 mm. The characteristics of the porous coating were derived from measurements on boiling in free convection, and the coating was formed on the surface of a tube 10 × 1 mm and 2015 mm long by sintering. The coating and tube materials were Kh18N10T steel. The coating particle diameter was about 60 μm, coating thickness about 0.22 mm, porosity about 70%. That coating represented a one-scale layer. The boiling features here were due mainly to the shape and size distribution of the vaporization centers.

The outside temperatures were recorded with 50 chromel-alumel thermocouples placed with a minimum pitch of 10 mm. A completely automated system was used.

Figure 1 shows the typical course of the time-averaged wall temperature $\overline{T}_w$, the heat-transfer coefficient, and the intensity S of the wall temperature fluctuation along the tube with the technically smooth surface. The instantaneous values T_w were averaged to derive $\overline{T}_w$. When the method was being developed, the realization time was estimated as required to give a reliable unbiased estimator for each of the statistical quanities. It is evident that $\overline{T}_w$ and α vary smoothly, so if one defines the cross section for the onset of boiling by the use of the averaged wall temperature profile, one can obtain only an approximate value for $(T_w-T_s)_{bo}$. Also S varied substantially along the length, and in the single-phase region it attained about 1.2°C, while in the boiling zone it fell to about 0.2°C, since the dispersion and the spectral density of the wall temperature fluctuations alter when boiling starts because the bubbles affect the boundary layer.

We conclude that the onset of boiling corresponds to a sharp reduction in S. The S distribution data on the boiling onset agree satisfactorily with the calculated $(T_w-T_s)_{bo}$ from Styushin's formula [4]. (Fig. 1). We used this method to measure $(T_w-T_s)_{bo}$ for water flowing in the tube at P = 0.1-6.0 MPa and ρw = 20-600 kg/m²·sec.

The coating with forced motion reduced the $(T_w-T_s)_{bo}$ considerably. Model concepts were used [5] in deriving the $(T_w-T_s)_{bo}$ dependence, for which boiling in a technically smooth tube begins when there is substantial temperature nonuniformity in the wall layer.

A vapor bubble begins to grow when the local superheating in the liquid at the point on the bubble surface furthest from the wall becomes equal to the value necessary from

$$\Delta T_\ell = \frac{4\sigma T_s}{r\rho'' D_{cr}}. \quad (1)$$

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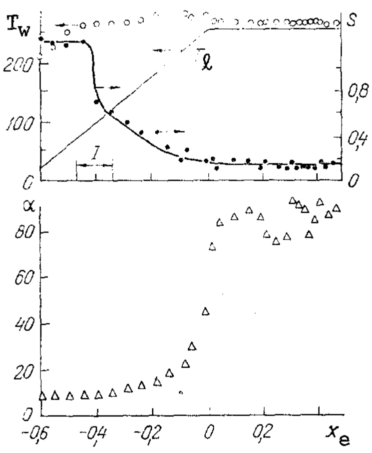

Fig. 1

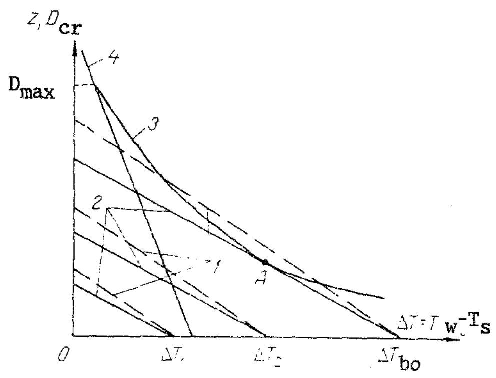

Fig. 2

Fig. 1. $\bar{T}_w$, S, and α in relation to x_e on transition to boiling in a technically smooth tube, P = 4.28 MPa, ρW = 610 kg/m²·sec, and q = 1170 kW/m²; I calculation on x_{bo} [4], $\bar{T}_w$ in °C, and α in kW/m²·K.

Fig. 2. Determining the onset of boiling on a porous-coated surface: 1, 2) temperature profiles in porous layer for free and forced convection correspondingly; 3) $D_{cr}(\Delta T)$; 4) temperature profile for $D_{cr} > D_{max}$.

The less remote layers in the nucleus are in contact with more superheated liquid layers.

The evaporation on a coated surface has some special features. The coating increases the thickness of the superheated wall layer because of the higher effective thermal conductivity λ_{ef} and reduced effects on it from turbulent pulsations in the subheated core of the flow by comparison with a technically smooth surface. With the coating, there are existing nucleation centers, and nucleation is favored, which means that the wall superheating corresponding to the boiling onset is lower. Nuclei are formed not as domes over depressions with radius R_{cr}, as assumed in [5], but as spheres with diameter D_{cr}.

If we assume that the coating has an ordered cubic structure, the effective thermal conductivity is [6]

$$\lambda_{ef} = \lambda_f \gamma + (1-\gamma)\left(\frac{1-\varepsilon}{\lambda_f} + \frac{\varepsilon'}{\lambda'} + \frac{\varepsilon''}{\lambda''}\right)^{-1}, \tag{2}$$

in which λ_f is the framework conductivity, ε porosity, ε'' and ε' the volume proportions of vapor and liquid in the coating, and λ' and λ'' the thermal conductivities of water and steam at the saturation temperature, while $\gamma = (1-\varepsilon^{1/3})^2$.

We assume that heat is transmitted by the porous layer only by conduction under free-convection conditions. Then the temperature will vary linearly over the porous layer in accordance with

$$T(z) = T_w - \frac{z}{\lambda_{ef}} q. \tag{3}$$

Here z is the distance from the heating surface at which the porous coating is deposited.

In forced motion, the effect from the overeheated core on the superheated wall layer means that the temperature profile is steeper. We assume for simplicity that it remains linear and incorporate the effects from the forced convection as follows:

$$T(z) = T_w - \frac{z}{\lambda ef} q(1 + f(\mathrm{Re}))^n, \tag{4}$$

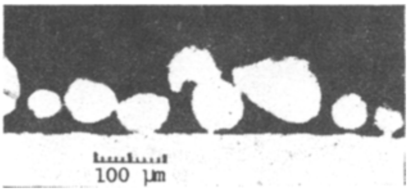

Fig. 3. Section of porous-coated tube, ×100.

in which $Re = Wd_e/\nu$, while $(1 + f(Re)^n$ is the correction for the forced motion, which is determined by experiment. Equation (4) implies that it becomes (3) for $W \to 0$, with the latter applicable for the conditions in a large volume.

Figure 2 shows the conditions for the onset of boiling at a coated surface. The superheating over the height of the porous layer for various $\Delta T = T_w - T_s$ is represented by the family of straight lines

$$z = l - m\Delta T, \tag{5}$$

in which ℓ is the thickness of the superheated wall layer and m governs the temperature gradient through the porous coating:

$$m = \frac{\lambda_{ef}}{q(1+f(Re))^n}. \tag{6}$$

Figure 2 also shows D_{cr} as a function of the local superheating (curve 3). Boiling can occur in the porous layer if $D_{cr} < D_{max}$, in which D_{max} is the size of the largest pore. Therefore, curve 3 has D_{max} as an upper bound. The point A common to both lines defines the boiling onset condition, while the abscissa $\Delta T_{bo} = (T_w - T_s)_{bo}$ is the minimum wall superheating at which boiling begins. At A,

$$\left(\frac{d(D_{cr})}{d(\Delta T)}\right)_A = \left(\frac{dz}{d(\Delta T)}\right)_A. \tag{7}$$

We use (4) and (1) to write (7) as

$$\frac{\lambda_{ef}}{q(1+f(Re))^n} = \frac{4\sigma T_s}{(T_0 - T_s)^2 \rho'' r}, \tag{8}$$

in which T_0 is the temperature corresponding to the point of contact between lines 2 and 3, which relates to the part of the bubble surface furthest from the wall:

$$z = D_{cr} = \frac{4\sigma T_s}{(T_0 - T_s)\rho'' r}. \tag{9}$$

Then

$$D_{cr} = \sqrt{\frac{4\lambda_{ef}\,\sigma T_s}{q(1+f(Re))^n \rho'' r}}. \tag{10}$$

We solve (4), (8), and (9) together to get the boiling-onset wall temperature:

$$T_w = T_s + 2\sqrt{\frac{\sigma T_s q(1+f(Re))^n}{\rho'' r \lambda_{ef}}}. \tag{11}$$

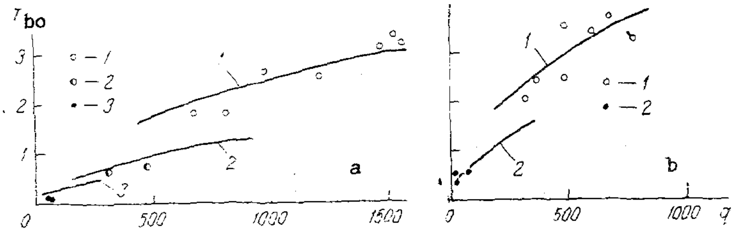

Fig. 4. Comparison of measurements on $(T_w-T_s)_{bo}$ in a coated tube with calculations from (14) and (15): a + P = 6 MPa: 1) W_0 = 0.81 m/sec; 2) 0.28; 3) 0.03; b) P = 1 MPa: 1) W_0 = 0.48 m/sec; 2) 0.03; T_{bo} in °C and q in kW/m^2.

Here f(Re) and n derived from experiment; (11) applies for

$$\frac{4\lambda_{ef}\sigma T_s}{q(1+f(\mathrm{Re}))^n\rho'' r} < D_{max}. \tag{12}$$

For $z = D_{max}$, the boiling onset temperature is found by solving (4) and (9) together:

$$T_w = T_s + \frac{4\sigma T_s}{\rho'' r D_{max}} + \frac{D_{max}}{\lambda_{ef}} q(1+f(\mathrm{Re}))^n. \tag{13}$$

D_{max} can be determined as follows. Water boils at a surface with a sintered porous coating made of stainless steel with the above structure under large-volume conditions for P = 0.1 MPa [7] when $(T_w-T_s)_{bo}$ = 2.5°C (q = 20,000 W/m^2, $\Delta T_{col} = (T_s-T_\ell) = 0$). We solve (13) for D_{max} to get $D_{max\ 1}$ = 35 μm and $D_{max\ 2}$ = 110 μm.

Figure 3 shows a coated tube at a magnification of 100 (section); $D_{max} \approx 110$ μm for the real structure. We now evaluate the reliability of the approach. In [7], it was found that large-volume water boiling at a porous-coated surface with the above characteristics, but made from copper, gave $(T_w-T_s)_{bo}$ less than 1°C. We substitute D_{max} = 100 μm and $\lambda_{ef} \approx 5.5$ W/m·K into (13), with the latter derived from (2), to get $T_w-T_s \approx 0.9$°C.

These results confirm the model in the limit of boiling in a large volume. The data for a coated tube in the parameter ranges and gave a correction for the forced flow, and the boiling-onset temperature formula became

$$T_w = T_s + 2\sqrt{\frac{\sigma T_s q(1+\mathrm{Re}\cdot 10^{-5})^{5.1}}{\rho'' r\lambda_{ef}}} \tag{14}$$

for $D_{cr} < D_{max}$,

$$T_w = T_s + \frac{4\sigma T_s}{D_{max}\rho'' r} + \frac{D_{max}}{\lambda_{ef}} q(1+\mathrm{Re}\cdot 10^{-5})^{5.1} \tag{15}$$

for $D_{cr} \geqslant D_{max}$,

$$D_{cr} = \sqrt{\frac{4\lambda_{ef}\sigma T_s}{q(1+\mathrm{Re}\cdot 10^{-5})^{5.1}\rho'' r}}$$

for $0 \leqslant \mathrm{Re} \leqslant 4.5\cdot 10^4$.

Figure 4 compares measured $(T_w-T_s)_{bo}$ with ones calculated from (14) and (15) for a coated tube. The formulas describe the measurements satisfactorily, and the latter enable one to examine how the mode parameters affect the wall superheating corresponding to boiling onset. Here $(T_w-T_s)_{bo}$ increases with the flow speed, the heat load, and as the pressure falls. It is evident that if the flow speed is low ($w_0 < 0.3$ m/sec), there is hardly any effect on $(T_w-T_s)_{bo}$.

The balance vapor content corresponding to the onset of boiling x_{bo} has a one-to-one relationship to $(T_w-T_s)_{bo}$ (14) and (15) give x_{bo} for a coated tube as

$$x_{bo} = -\frac{c_p}{r}\left(\frac{q}{\alpha_{conv}} - 2\sqrt{\frac{\sigma T_s\, q\,(1+\mathrm{Re}\cdot 10^{-5})^{5,1}}{\rho'' r \lambda_{ef}}}\right) \quad (16)$$

for $D_{cr} < D_{max}$,

$$x_{bo} = -\frac{C_p}{r}\left(\frac{q}{\alpha_{conv}} - \frac{4\sigma T_s}{D_{max}\,\rho'' r} - \frac{D_{max}}{\lambda_{ef}}\, q\,(1+\mathrm{Re}\cdot 10^{-5})^{5,1}\right) \quad (17)$$

for $D_{cr} \geqslant D_{max}$, $0 \leqslant \mathrm{Re} \leqslant 4{,}5\cdot 10^4$.

Boiling begins in a coated tube with lower wall superheating, less liquid underheating (because of the higher α_{conv} in the coated tube), and larger x_{bo}.

These results are of some interest, particularly for calculations on mass transfer in steam-generating channels.

NOTATION

z, coordinate; x_{bo} and T_{bo}, relative enthalpy and temperature for boiling onset; S, temperature pulsation range; σ, surface tension; r, latent heat of vaporization; ρ, density; D_{cr}, critical vapor nucleus diameter; λ_{ef}, effective thermal conductivity, q, heat flux density; W_0, circulation speed; ν, kinematic viscosity; d_{eq}, equivalent diameter; D_{max}, maximum pore size in coating; α_{conv}, convective heat-transfer coefficient; T_w, wall temperature; $\bar{T}_w$, wall temperature averaged with respect to time; T_ℓ, liquid temperature; d_e, equivalent diameter.

LITERATURE CITED

1. N. N. Savkin, A. S. Komendantov, and Yu. A. Kuzma-Kichta, Teploénergetika, No. 5, 67-69 (1988).
2. V. M. Azarskov, G. N. Danilova, B. B. Zemskov, et al., Abstracts on Heat and Mass Transfer at MMF [in Russian], Minsk (1988), pp. 6-8.
3. S. L. Solov'ev and E. G. Shklover, Abstracts on Heat and Mass Transfer at MMF [in Russian], Minsk (1988), pp. 180-182.
4. A. M. Kutepov, L. S. Sterman, and N. G. Styushin, Hydrodynamics and Heat Transfer in Steam Formation [in Russian], Moscow (1986).
5. Y. Y. Hsu, Int. J. Heat Mass Transfer, 1, No. 3, 207-216 (1962).
6. G. N. Dul'nev and Yu. M. Zarichnyak, Thermal Conductivities of Mixtures and Composites [in Russian], Leningrad (1974).
7. Yu. A. Kuzma-Kichta, V. N. Moskvin, and D. N. Sorokin, Teploénergetika, No. 3, 53-54 (1982).