CORRELATION OF HEAT TRANSFER DATA ON STABLE FILM POOL BOILING AT VERTICAL SURFACES FOR FREE CONVECTION

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Experimental heat transfer data on film boiling of a liquid at the vertical surfaces of a heater are analyzed and correlated.

A considerable amount of experimental data has recently been accumulated on heat transfer in film boiling of a liquid at vertical heating surfaces [1-4]. It has been established that the heating surface is separated from the liquid by a vapor film whose thickness is considerably less than the height of the heating surface. The motion of the vapor in the film is apparently turbulent [1] and is due to buoyancy forces. The kinematic picture of the film pool boiling process is similar in many respects to that observed in natural convection of a liquid near heated heating surfaces. The difference relates to the participation in the film boiling process of two interacting phases with substantially different densities, and to the presence of a phase transformation.

In free-convection heat transfer [5] the characteristic parameters are the Prandtl number $(\mathrm{Pr}=\nu/a)$ and Grashof number $(\mathrm{Gr}=(gl^3/\nu^2)\beta\Delta t)$. In the latter the relative temperature change for unit volume of a medium experiencing free convection may be written as follows:

$$\beta\Delta t \equiv \beta(t - t_\infty) \equiv (\gamma_\infty - \gamma)/\gamma. \tag{1}$$

In the case of film boiling in a large volume the analogous parameter is

$$\mathrm{Ga}''\left(\frac{\gamma-\gamma''}{\gamma''}\right) \equiv \frac{gl^3}{\nu''^2}\left(\frac{\gamma-\gamma''}{\gamma''}\right). \tag{2}$$

Therefore, in the general case of convective heat transfer in film boiling under conditions of free convection, the following functional relation may be written:

$$\mathrm{Nu}_k'' = F_1\left\{\mathrm{Ga}''\left(\frac{\gamma-\gamma''}{\gamma''}\right);\ \mathrm{Pr}''\right\}. \tag{3}$$

Since the Pr" numbers of the vapors investigated in [1-4] are close to unity, it is inconvenient to seek a dependence of heat transfer on Pr". Therefore, Eq. (3) is simplified and reduced to the form

$$\mathrm{Nu}_k'' = F_2\left\{\mathrm{Ga}''\left(\frac{\gamma-\gamma''}{\gamma''}\right)\right\}. \tag{4}$$

The choice of the characteristic length l appearing in (4) requires special consideration. It has been noted [6, 7] that heat transfer in free convection for gases in narrow vertical slots does not depend on the vertical dimension of the slot, but varies appreciably with its width. The heat transfer was likewise found to be independent of the height of the heating surface in tests on the film boiling of liquids in long vertical tubes [1-4]. By analogy, we can take the average vapor film thickness δ [1] as the characteristic linear dimension in (4), which then assumes the form

$$\mathrm{Nu}_{k\delta}'' = F_3\left\{\mathrm{Ga}_\delta''\left(\frac{\gamma-\gamma''}{\gamma''}\right)\right\}, \tag{5}$$

where

$$\mathrm{Nu}_{k\delta}'' = \alpha_k\delta''/\lambda''; \quad \mathrm{Ga}_\delta'' = g\,\delta''^3/\nu''^2.$$

It has been established [4] that, in film boiling, the motion of the vapor at a vertical heating surface takes the form of a pulsating flow of pear-shaped contiguous bubbles rising to the upper part of the surface. For the rate of rise of a single spherical bubble in a liquid with no surface-active agents present and bubbles of moderate size, we have the following expression [8-10]:

$$W'' = \frac{1}{36}\frac{(\gamma-\gamma'')D^2}{\mu}. \tag{6}$$

If interaction of the bubbles is neglected, then for the average thickness [1] of the vapor film we may write:

$$\delta'' = DF_4(q/r\gamma''W''). \tag{7}$$

The bubble diameter may be determined from the empirical formula obtained by one of the authors of [12] and checked for film boiling on a horizontal surface in a large volume of liquid [11]:

$$D = 4.7\,[\sigma/(\gamma - \gamma'')]^{0,5}. \tag{8}$$

Substituting values of W" and D from (6) and (8) into (7), we have

$$\delta'' = 4.7\left(\frac{\sigma}{\gamma-\gamma''}\right)^{0.5} F_4\left(36\,\frac{q\mu}{r\gamma''\sigma}\right) = \mathrm{const}\left(\frac{\sigma}{\gamma-\gamma''}\right)^{0.5} F_5\left(\frac{q\mu}{r\gamma''\sigma}\right). \tag{9}$$

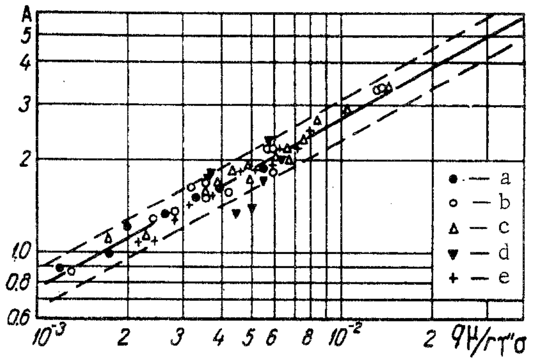

Fig. 1. Correlation of experimental data on the mean thickness of the vapor film in a vertical tube 80 mm tall and 3 mm in diameter: a) ethyl ether, b) ethyl alcohol, c) normal hexane, d) distilled water, e) benzene $\left(A = \delta\left(\frac{\sigma}{\gamma-\gamma''}\right)^{0.5}\right)$.

The specific form of the function $F_5\ (q\mu/r\gamma''\sigma)$ and the value of the constant in (9) can be determined by experiment. Figure 1 shows a correlation based on (9) of the data of [1] on the mean vapor film thickness in film boiling for various liquids at atmospheric pressure. The maximum scatter of the experimental points is ±15%.

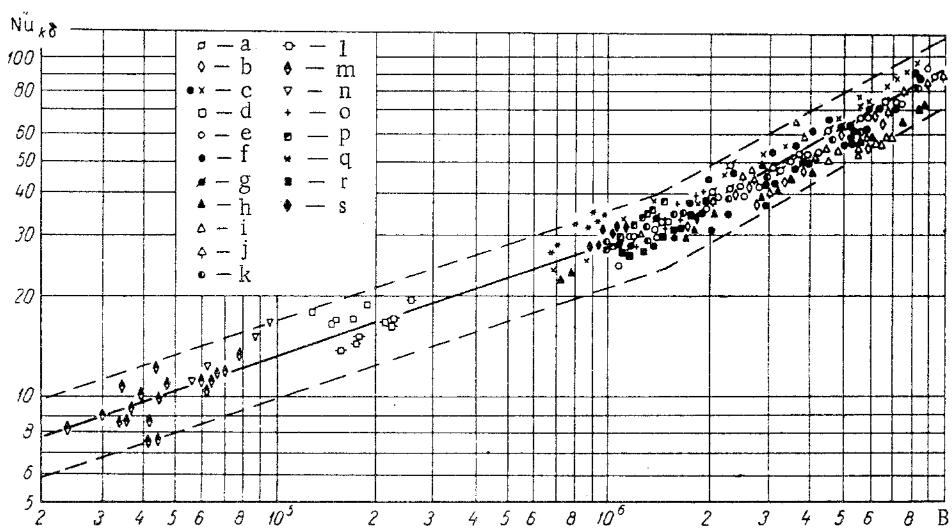

Fig. 2. Correlation of experimental heat transfer data on film boiling of liquids in vertical tubes $\left(B \equiv Ga''_\delta\left(\frac{\gamma-\gamma''}{\gamma''}\right)\right)$:

Benzene: a) d = 3 mm, l = 47 mm, p = 98.1 · 10^3 n/m^2 [1]; b) 6, 283, 98.1 · 10^3 [2]; c) 6, 287, 98.1 · 10^3 [2]; d) 12.7 · 117.6, 98.1 · 10^3 [3]. Ethyl alcohol: e) 3.37, 98.1 · 10^3 [1]; f) 6, 276, 98.1 · 10^3 [2]; g) 6, 287, 98.1 · 10^3 [2]; h) 3, 60, 98.1 · 10^3 [1]. Ethyl ether: i) 6, 260, 98.1 · 10^3 [2]; j) 6, 287, 98.1 · 10^3 [2]. Normal hexane: k) 3, 47, 98.1 · 10^3 [1]. Carbon tetrachloride: l) 12.7, 117.6, 98.1 · 10^3 [3]. Methyl alcohol: m) 9.5, 136.7, 98.1 · 10^3 [3]; n) 12.7, 116.7, 98.1 · 10^3 [3]. Ethyl alcohol: o) 6, 276, 262 · 10^3 [3]; p) 6, 276, 490 · 10^3 [2]; q) 6, 276, 98.1 · 10^3 [2]; r) 6, 283, 490 · 10^3 [2]; s) 6, 283, 981 · 10^3.

The straight line drawn through the experimental points corresponds to the equation

$$\delta'' = 31\left(\frac{\sigma}{\gamma-\gamma''}\right)^{0.5}\left(\frac{q\mu}{r\gamma''\sigma}\right)^{0.53}. \tag{10}$$

Figure 2 shows a correlation in the coordinates of (5) of the experimental data of [1-4] on heat transfer in film boiling at vertical surfaces. In all cases the mean thickness δ" of the vapor film was calculated from (10). Only the data from [3] relating to stable film boiling were used for analysis in system (5). The graph shows that the experimental data can be correlated correct to ±25%. Since in film boiling at a vertical surface the flow of the vapor layer is evidently very turbulent, the bulk of the vapor in the turbulent vapor film, with the exception of a thin laminar sublayer, is at saturation temperature. Therefore the physical properties of the liquids and their saturated vapors in (5) and (10) relate to saturation temperature. The lines drawn through the experimental points on the graph of Fig. 2 can be described by the following equations:

$$\mathrm{Nu}''_{k\delta} = 0.28\left[\mathrm{Ga}''_{\delta}\left(\frac{\gamma-\gamma''}{\gamma''}\right)\right]^{0.33} \quad \text{for } 2\cdot 10^{4} < \mathrm{Ga}''_{\delta}\left(\frac{\gamma-\gamma''}{\gamma''}\right) < 1.4\cdot 10^{6};$$
$$\mathrm{Nu}''_{k\delta} = 0.0094\left[\mathrm{Ga}''_{\delta}\left(\frac{\gamma-\gamma''}{\gamma''}\right)\right]^{0.57} \quad \text{for } 1.4\cdot 10^{6} < \mathrm{Ga}''_{\delta}\left(\frac{\gamma-\gamma''}{\gamma''}\right) < 1.5\cdot 10^{7}. \qquad (11)$$

NOTATION

ν, a – kinematic viscosity and thermal diffusivity of medium; γ, γ_∞ and t, t_∞ – density and temperature of liquid at any point in the medium and at an infinite distance from the heating surface; β – coefficient of volume expansion; l – characteristic linear dimension; $\mathrm{Nu}''_k = \alpha_k l/\lambda''$ – Nusselt number for vapor phase; α_k, λ'' – convective heat transfer coefficient and thermal conductivity of vapor; W" – rate of rise of a single vapor bubble in liquid; D – diameter of a vapor bubble; μ – viscosity of liquid; q – specific heat flux at heating surface; r – latent heat of vaporization; σ – surface tension of the liquid. The superscript " denotes parameters of the vapor phase, other parameters relate to the liquid.

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