THEORY OF HEAT TRANSFER IN NUCLEATE BOILING

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Nucleate boiling heat transfer may be considered as heat transfer to the liquid near a stagnation point. Using boundary-layer theory and the laws of free turbulence, the authors obtain formulas containing two empirical constants.

It has been established by experiment that more than 98% of the heat in nucleate boiling is transmitted directly to the liquid flowing over the heat-transfer surface. It is therefore necessary, in the first instance, to examine the process of direct heat transfer between liquid and body surface.

The statistical mean linear dimension of a square cell corresponding to one active vaporizing center can be evaluated from the formula

$$l \approx \sqrt{\frac{r\gamma''}{q}\psi V_0 u}, \tag{1}$$

where the separation volume of the bubbles is of the order

$$V_0 \approx (\sigma/(\gamma' - \gamma''))^{3/2}, \tag{2}$$

and the maximum frequency

$$u_{\max} \approx v''_{\max}\sqrt{(\gamma' - \gamma'')/\sigma}. \tag{3}$$

Formula (3) correctly reflects, both qualitatively and quantitatively, the most recent experimental results. Measured values of the statistical mean bubble formation frequency constitute approximately 50-70% of u_{max} [1]. Calculations based on the above formulas indicate that even for moderate thermal flux the size of the elementary cell in nucleate boiling of a saturated liquid is commensurate with the bubble diameter, i.e., for developed nucleate boiling

$$l \approx \sqrt{\sigma/(\gamma' - \gamma'')}. \tag{4}$$

On the other hand, the cell size cannot be appreciably less than (4), otherwise strong coalescence of neighboring bubbles and transition to film boiling must take place. Condition (4) may obtain for large, though subcritical, heat fluxes because of phase shift in the cycle of bubble formation at neighboring centers. The order of thickness of the thermal boundary layer in the liquid can be evaluated from the relation $\delta \approx \lambda/q$.

Hence

$$\frac{\delta}{l} \approx \frac{\lambda}{q}\sqrt{\frac{\gamma' - \gamma''}{\sigma}}. \tag{5}$$

For example, for water at low pressure, this ratio is less than 0.005 when q = 23 300 $w \cdot m^{-2}$. Boundary-layer theory may therefore be used as a first approximation in analyzing the cell. The heat transfer process in nucleate boiling can be represented schematically as in Fig. 1.

Liquid flow of this kind can be identified with flow in the stagnation region of a blunt-nosed body. In a region of vaporizing centers, part of the liquid is transformed into vapor bubbles, while the bulk of the liquid is carried, together with the vapor bubbles, into the main volume. As a result, strong circulation is created, which also largely determines the velocity of the liquid reaching the surface, and consequently the intensity of heat transfer.

The flow rate of liquid towards a typical cell is of the order $G' \approx (1+\xi)q/r$, where ξ is the coefficient of the entrained mass. For mushroom-shaped bubbles ξ may reach a value of 10. The approach velocity of the liquid will be of the order

$$w' \approx \frac{q}{r\gamma'}\frac{1+\xi}{1-\varphi}.$$

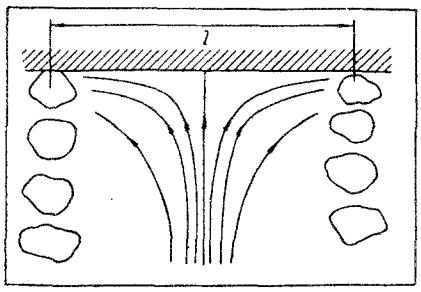

Fig. 1. Diagram of heat transfer process in nucleate boiling.

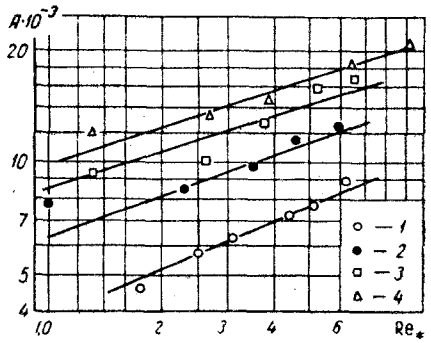

Fig. 2. Experimental verification of Eq. (9) for water:

1—p = 98 newtons·cm^{-2}; 2—490; 3—730; 4—980. $A = Nu_*^2/Pr^{1/3}Re_*$

Thus, the velocity of liquid flowing towards a cell may be two or more orders greater than the value corresponding to the rate of vaporization. Even in this case, however, the Reynolds number $Re = \omega' l/\nu$ is appreciably less than its critical value for ordered flow. Therefore the usual laws of turbulent transfer are not applicable, although the vaporization process undoubtedly makes the boundary layer in question turbulent. The analytical solution of the equations of the thermal boundary layer in a stagnation point region can be expressed in the form

$$Nu_* = c\,Pr^{1/3}\,Re_*^m, \tag{6}$$

where

$$Nu_* = \frac{\alpha l}{\lambda'}, \quad Re_* = \frac{q}{r\gamma'}\frac{l}{\nu'}, \quad Pr = \frac{\mu' c_p'}{\lambda'}, \quad l = \sqrt{\frac{\sigma}{\gamma' - \gamma''}}.$$

For a laminar boundary layer, m = 1/2 and

$$Nu = c\,Pr^{1/3}\,Re^{1/2}. \tag{7}$$

If we take, as a first approximation, that $\mu_T \sim \rho'\omega' l$; $\lambda_T \sim gc'_p\rho'\omega' l$, then (7) can be written in the form

$$Nu_* \simeq c_1\,Pr^{1/3}\,Re_*^{1/2}\,\frac{(1 + c_2\,Pr\,Re_*)^{2/3}}{(1 + c_2\,Re_*)^{1/6}}. \tag{8}$$

Here coefficients c_1 and c_2 may, in the general case, be functions of γ''/γ', and the properties of the heating surface (e.g., characteristics such as the wetting contact angle).

When Pr ≈ 1.0, it follows from (8) that

$$Nu_*/Re_* = c_1^2 + c_3\,Re_*. \tag{9}$$

The experimental results of [2], expressed in terms of the coordinates of (9), are presented in Fig. 2. It is evident that in the main part of the range of Re_* a linear relation holds. Here coefficient c_3 is practically constant, while c_1 increases somewhat with increase in γ''/γ'. But for very small values of γ''/γ', and for near critical pressure, considerable deviations from Eq. (9) arise.

Fig. 3 gives the most recent experimental heat transfer data, taken over a wide range of pressures, and generalized in the form (6). The graph also shows heat transfer results with air bubbled through a porous plate. It is clear that all experimental points for the cases examined are satisfactorily close to the curves $Nu_* = 74\,Re_*^{0.7}\,Pr^{1/3}$ (a) and $Nu_* = 25\,Re_*^{0.7}\,Pr^{1/3}$ (b).

The difference in the multiplying factors in these formulas is probably attributable to the presence in the second case of complex physical and chemical activity at the heat transfer surface.

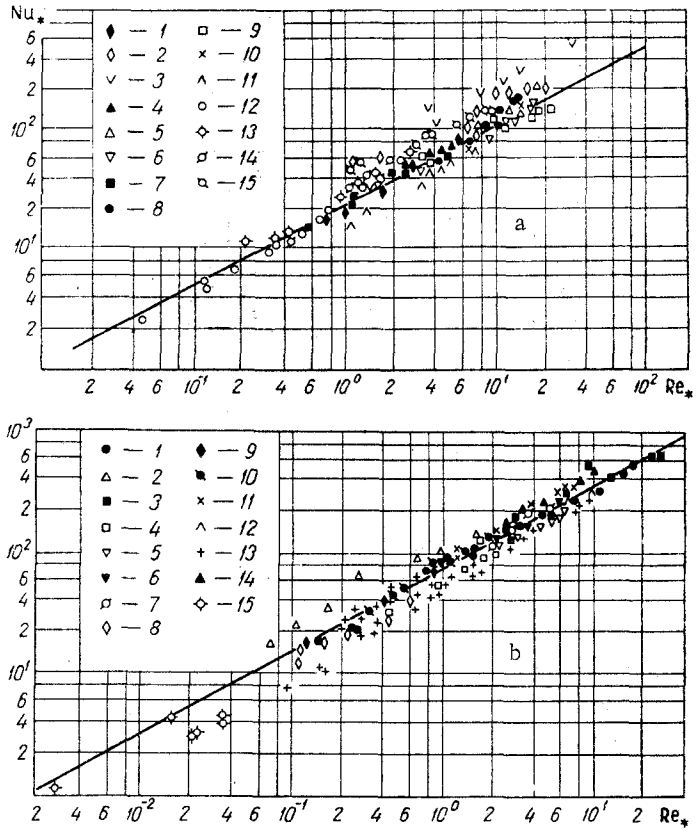

Fig. 3. Generalized experimental data on formula (6) for (a) boiling water, alcohol, and freon-22, and (b) boiling specific hydrocarbons ($Nu_* = \alpha\sqrt{\sigma/(\gamma'-\gamma'')}/\lambda$; $Re_* = q\sqrt{\sigma/(\gamma'-\gamma'')}/\gamma r\nu$): a) results of [3] (water: 1 – 252 n · cm^{-2}; 2 – 980; 3 – 1970); results of [2] (water: 4 – 10 n · cm^{-2}; 5 – 98; 6 – 490; 7 – 1960; alcohol: 8 – 9.8 n · cm^{-2}; 9 – 30; 10 – 49; 11 – 98; 12 – 490); results of [4] (freon-22: 13 – 98 n · cm^{-2}); results of [5] (14 – water – air; 15 – alcohol – air); b) results of [6](benzene: 1 – 35.3 n · cm^{-2}; 2 – 182; 3 – 320; n-propane: 4 – 116.5 n · cm^{-2}; 5 – 203; 6 – 249; n-heptane: 7 – 10.1 n · cm^{-2}; 8 – 79; 9 – 148; n-heptane: 10 – 79 n · cm^{-2}; 11 – 215); results of [7] (benzene: 12 – 9.8 n · cm^{-2}; 13 – 35.2; 14 – 79; 15 – 207).

Thus, the extension of boundary-layer theory to the heat-transfer process in nucleate boiling gives a correct evaluation of the basic heat-transfer mechanism in these complex conditions, and seems a reasonable basis on which to build a more elaborate theory of boiling heat transfer.

NOTATION

l – linear dimension of cell; r – heat of vaporization; γ – specific weight of medium; ρ – density of medium; V_0 – bubble separation volume; u – bubble separation frequency; v''_{max} – bubble rise velocity; σ – surface tension; δ – boundary layer thickness; λ – thermal conductivity; G – mass flow of liquid; ξ – additional mass coefficient; ω – approach flow velocity; ν – coefficient of kinematic viscosity; μ – coefficient of dynamic viscosity; c_p – specific heat of medium; φ – vapor content by volume; g – acceleration of gravity; q – thermal flux density; ψ – coefficient to allow for relative change in bubble volume; superscripts: ' – liquid, " – vapor.

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