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NUCLEATE BOILING

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The study deals with the effect of the surface conditions on the nucleate boiling curve. A relation is proposed which describes the complete nucleate boiling curve.

Nucleate boiling is of extraordinary practical significance, more than other modes of heat dissipation, inasmuch as it facilitates dumping of large thermal fluxes at relatively low temperature heads. At the same time, this is one of the most intricate heat transfer processes and no complete theory of it has yet been developed which takes into account all the factors influencing the intensity of heat transfer.

One basic difficulty in constructing a theory of nucleate boiling is the unavailability of sufficient information about the effect of conditions at the heat emitting surface on nucleate boiling, which has been shown already [1, 2] to largely determine the intensity of heat transfer. On the one hand, the nucleate boiling curve is conservative with respect to such parameters as the gravitation constant, the velocity of the main mass flux of liquid, and particularly the liquid underheating (which substantially affects the pattern of nucleate boiling), parameters seemingly important from the standpoint of the heat dissipation mechanism on the basis of which various models of the process have been constructed. On the other hand, the position and the slope of the nucleate boiling curve are largely determined by the roughness of the heating surface. Indeed, a change in the surface roughness can change the intensity of heat dissipation by a factor of 5-10. Since the mode of nucleate boiling depends so much on the surface roughness, it should be interesting to find out how the boiling curve will change as the roughness dimension and the number of active vapor formation centers decrease toward zero, i.e., as the ideal case of a surface without vapor formation centers and a liquid without dissolved gas is being approached.

It is well known that an increase of the roughness of the heating surface causes the boiling curve to shift toward lower underheat temperatures. Beginning with a class 6-7 surface finish, however, further increase of the roughness hardly affects the position of the nucleate boiling curve. Surfaces with such a treatment are called "technical-grade surfaces." Most theoretical relations pertaining to heat emission during nucleate boiling are generalizations of data obtained with such surfaces. As the roughness decreases, vapor formation at the surface becomes more difficult and in most experiments [1] the slope of the boiling curve has been found to increase.

It is nowadays universally assumed that, under real conditions, surface irregularities filled with gas constitute the vapor formation centers. The dimension of critical vapor formating nucleus is in this case equal to the radius of the opening of a surface cavity [3, 4] which constitutes such a vapor formation center, namely

$$R_{\mathrm{cr}} = 2\sigma T''/(r\rho''\Delta T). \tag{1}$$

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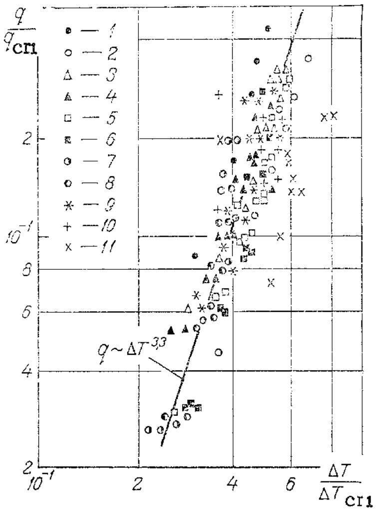

Fig. 1. Generalization of experimental data [15] on nucleate boiling of water: 1) 1 bar; 2) 4.5; 3) 9.8; 4) 14.8; 5) 19.4; 6) 29.5; 7) 49; 8) 73; 9) 98; 10) 147; 11) 196 bars.

As the pressure drops, the magnitude of a critical vapor forming nucleus according to expression (1) increases and this depletes the heating surface of vapor formation centers. This trend allows us to approach the idealized pattern of boiling at the heating surface, without vapor formation centers, if the object of the study is boiling of degased liquids at polished surfaces under subatmospheric pressures. Earlier studies [5, 6] have shown that, when the superheat degrees and the corresponding thermal flux prior to boiling satisfy the conditions

$$\Delta T \geqslant \Delta T_{\text{cr3min}},\quad q > q_{\text{cr2}}, \tag{2}$$

no nucleate boiling will occur at all and the first formation of the vapor phase after one-phase convection will lead to formation of a stable vapor film (third boiling crisis) at the surface. When conditions (2) are not satisfied, e.g., owing to the effect of the hydrodynamic conditions in the boundary layer of liquid on the superheating prior to boiling [7], then the appearance of the vapor phase after one-phase convection should lead to nucleate boiling.

In studying the boiling of liquids under subatmospheric pressures, several authors [8-10] have observed an anomalous trend of nucleate boiling curves: an increase of the thermal flux at the heat emitting surface not accompanied by a corresponding increase of the mean temperature head, i.e., vertical straight lines in the (q, ΔT) plane approximating the experimental data. Moreover, the lower the pressure, the wider is the range where q does not depend on ΔT and the narrower is the range of the boiling curve corresponding to the natural distribution of vapor formation centers. A diminution of the vapor formation centers was found to cause the segment of the curve corresponding to q independent of ΔT to shift toward a higher superheat and its regular segment to become shorter. In another study [10] of boiling at surfaces largely depleted of vapor formation centers, the temperature head was found to be independent of the thermal flux throughout the nucleate boiling mode up to the first critical thermal flux.

Therefore, on the basis of experimental data pertaining to the effect of surface roughness on nucleate boiling and data pertaining to the boiling of liquids under subatmospheric pressures, one can hypothesize that the limiting nucleate boiling curve, with decreasing size and number of vapor formation centers, will be a vertical line in the (q, ΔT) plane described by the equation

$$\Delta T = \Delta T_{\text{cr1}},\quad q_* \leqslant q \leqslant q_{\text{cr1}}. \tag{3}$$

A further diminution of the vapor formation centers will lead to formation of unstable vapor films, i.e., to transition boiling at the heating surface. The temperature head will be independent of the thermal flux during nucleate boiling also when boiling occurs at a surface with vapor formation centers of exactly one size all [11]. In this case the superheat independent of the thermal load can be determined from expression (1). This is also what the experiments [12] with heat emission near a single vapor formation center reveal.

Thus, the range over which the nucleate boiling curve changes depending on the surface roughness is bounded on the left-hand side by the boiling curve for technical-grade heating surfaces, where a further increase of the roughness will have almost no effect on the position of the nucleate boiling curve. On the right-hand side this range is bounded by the limiting nucleate boiling curve according to expression (3).

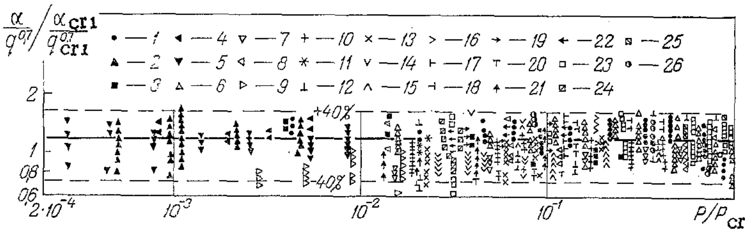

Fig. 2. Generalization of experimental data on nucleate boiling of various liquids: water: 1) [15]; 2) [9]; 3) [17]; 4) [21]; 5) [18]; ethanol: 6) [15]; 7) [19]; 8) [17]; 9) [18]; benzene: 10) [20]; 11) [22]; 12 [17]; diphenyl: 13) [20]; Freon-142: 14) [23]; Freon-22: 15) [23]; 16) [24]; Freon-12: 17) [24]; 18) [25]; 19) [26]; 20) [23]; Freon-21: 21) [27]; Freon-113: 22) [25]; nitrogen: 23) [28]; 24) [29]; 25) [30]; hydrogen: 26) [30].

The limiting curve can be used as the reference for comparing the effect of surface roughness on the nucleate boiling curves for various liquids under various pressures. The first crisis in heat transfer as the characteristic point will be selected since satisfactory relations are available for calculating its parameters. The expression for the first critical thermal flux, according to the hydrodynamic model [13] with the fraction of the heat carried away through the liquid [14] taken into account, is

$$q_{\mathrm{cr1}} = 0{,}14 r \rho''^{1/2} [\sigma g (\rho - \rho'')]^{1/4} + 10^{-5} (\sigma \lambda T'')^{1/2} \nu^{-1/4} (\sigma/\rho)^{3/8} [\sigma/kT \ln (NkT/h)]^{9/16}, \tag{4}$$

and the expression for the superheat during the first crisis in heat transfer [14] is

$$\Delta T_{\mathrm{cr1}} = 0.5 (\sigma T''/\lambda)^{1/2} \nu^{1/4} (\sigma/\rho)^{1/8} [\sigma/kT \ln (NkT/h)]^{3/16}. \tag{5}$$

The data shown in Fig. 1 [15] pertain to nucleate boiling of water under various pressures, referred to the parameters of the first boiling crisis and calculated according to relations (4) and (5). Since expression (5) for ΔT_{cr_1} is based on the mechanism of vapor film formation during transition boiling and $q_{\mathrm{cr}_1}/q_{\mathrm{cr}2} \simeq$ const [16], a similar generalization of experimental data is evidently possible for the transition mode of boiling.

For comparing various liquids with respect to heat transfer during nucleate boiling we will utilize the fact that for most liquids the coefficient of heat transfer α at technical-grade surfaces during fully developed boiling is proportional to $q^{0.7}$. The data of several authors [9, 15, 17-30] on heat transfer during nucleate boiling of various liquids as a function of the referred pressure are shown in Fig. 2. These experimental data can, within an accuracy of ±40%, be described by the relation

$$\alpha = 1.2 q^{0,7} \alpha_{\mathrm{cr1}}/q_{\mathrm{cr1}}^{0,7}, \tag{6}$$

covering the entire pressure range, where $\alpha_{\mathrm{cr1}} = q_{\mathrm{cr1}}/\Delta T_{\mathrm{cr1}}$ with q_{cr1} and ΔT_{cr1} calculated according to expressions (4) and (5) respectively. It is interesting to note that a satisfactory generalization of experimental data has been possible here without considering the mechanism of nucleate boiling, especially as relations (4) and (5) are based on models which regard crisis boiling as a phenomenon qualitatively different from nucleate boiling. The better the relations for the parameters of crisis boiling fit the experimental data, obviously, the more accurately will a relation of type (6) describe the experimental data on nucleate boiling. Such a satisfactory generalization evidently indicates that, in the first approximation, the roughness of a surface (at least a technical-grade surface) influences the heat dissipation during nucleate boiling of various liquids under various pressures in the same manner and that the critical heat transfer parameters contain all the information about the pressure dependence of the developed nucleate boiling mode.

With this conclusion, we can now proceed to describe the entire nucleate boiling curve by a relation in which no physical properties of the liquid and of the vapor appear directly, and to plot it through the characteristic points: beginning of vapor formation (q_*, ΔT_*) and first crisis in heat transfer (q_{cr1}, ΔT_{cr1}). The roughness of real surfaces, describable by the model of a normal random process [31], influences the nucleate boiling curve through the number of active vapor formation centers. The dependence of this number on the superheat of the surface is also an exponential one [32]. For describing the entire nucleate boiling curve has been chosen the expression

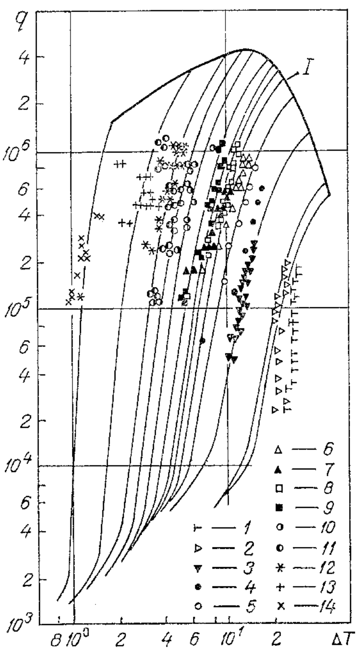

Fig. 3

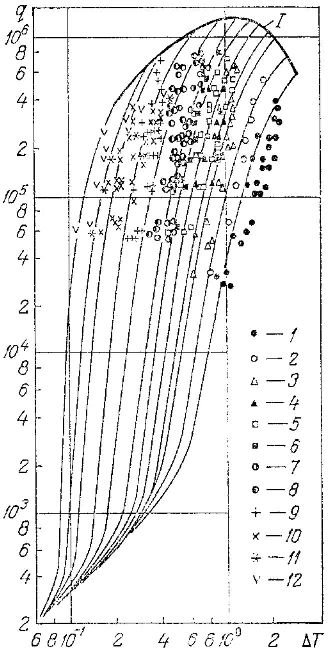

Fig. 4

Fig. 3. Comparison of calculation according to relation (7) and data on boiling of water: experiments [8]; 1) 0.06 bar, 2) 0.1; 3) 1; experiments [15]; 4) 1 bar, 5) 4.5; 6) 9.8; 7) 14.8; 8) 19.4; 9) 29.5; 10) 49; 11) 73; 12) 98; 13) 147; 14) 196 bar; I) calculation according to relations (4) and (5); q (W/m^2), ΔT (K).

Fig. 4. Comparison of calculations according to relation (7) and data on boiling of ethanol [15]: 1) 1 bar, 2) 3; 3) 5; 4) 7; 5) 10; 6) 14.7; 7) 19.4; 8) 29.4; 9) 39.4; 10) 49; 11) 53.4; 12) 58.8 bar; I) calculation according to relations (4) and (5).

$$q = q_c + q_{cr1}\exp\left(-1.2\,\frac{\Delta T_{cr1} - \Delta T}{\Delta T - \Delta T_*}\right), \tag{7}$$

which satisfies the boundary conditions

$$q|_{\Delta T=\Delta T_{cr1}} \simeq q_{cr1}, \quad q|_{\Delta T=\Delta T_*} = q_*.$$

Several authors [1] studying the nucleate mode of boiling have noticed a "hysteresis," where the superheat prior to boiling and the heat emission during nucleate boiling are both different depending on whether they have been measured during an increase or a decrease of the thermal flux. A relation of type (7), containing parameters which characterize the transition from convection to nucleate boiling, takes such a factor as hysteresis at least qualitatively into account.

The problem of superheating prior to boiling has thus far not been explored thoroughly enough so that no satisfactory expressions are available for calculating ΔT_*. When using expression (7) for describing data on steady-state nucleate boiling at technical-grade surfaces, in this case the reproducibility of data being satisfactory, one must select as one characteristic point on the curve the superheat at which nucleate boiling ceases and transition to one-phase convection occurs. Technical-grade surfaces (class 6-7 finish) are characterized by 6-10 μm large asperities [31], which correspond to 3-5°C superheat for water under a pressure of 1 atm according to relation (1). This is close to the experimental values of ΔT_* when boiling ceases. Experimental studies of boiling have revealed that the pressure dependence of ΔT_* is weaker than according to relation (1) and that $\Delta T_* \sim P^{-0.3}$ [33]. For calculating the superheat at the cessation of boiling has been chosen the relation

$$\Delta T_* = 1.2\cdot 10^{-3} T_{cr}(P/P_{cr})^{-0.3}, \tag{8}$$

with the numerical factor matched so that $\Delta T_* = 4°$ for water under a pressure of 1 atm.

Calculations according to relation (7) are compared in Figs. 3 and 4 with data for water and ethanol [15] under various pressures. Here q_{cr1}, ΔT_{cr1}, and ΔT_* have been calculated according to relations (4), (5), and (8) respectively, while q_c has been calculated according to the equation of one-phase convection at the corresponding superheat. The data here can be accurately described by relation (7) for various pressures, this relation taking into account the change in the slope of the boiling curve with a change in pressure. The graph in Fig. 3 also includes data in study [8]. The lower segments of the boiling curves corresponding to subatmospheric pressures are vertical straight lines, the upper segments of these curves correspond to a normal distribution of vapor formation centers and can also be accurately described by relation (7).

Furthermore, relation (7) can evidently also be used for describing the entire nucleate boiling curve in the case of forced flow. Then q_c, ΔT_*, q_{cr1}, and ΔT_{cr1} must be calculated according to the corresponding relations for forced flow.

In conclusion, it ought to be noted that a description of the entire nucleate boiling curve by relation (7) is only the first step. A more thorough accounting for the effect of surface conditions on nucleate boiling requires information about the dependence of ΔT_{cr1}, ΔT_*, and q_{cr1} on the roughness and the properties of the heat emitting surface. As of now, these problems have not yet been studied experimentally with sufficient thoroughness.

NOTATION

q, thermal flux; q_*, thermal flux at which the liquid boils after one-phase convection; q_c, thermal flux during one-phase convection; q_{cr1}, q_{cr2} are respectively the first and the second critical thermal flux; T'', saturation temperature; ΔT, superheat of the heating surface relative to the saturation temperature; ΔT_*, superheat prior to boiling of the liquid after one-phase convection; ΔT_{cr1}, superheat during the first boiling crisis; ΔT_{cr3min}, minimum superheat at which the third boiling crisis can occur; P, pressure; P_{cr}, critical pressure; α, heat transfer coefficient during nucleate boiling; R_{cr}, radius of a critical vapor forming nucleus; σ, coefficient of surface tension; r, latent heat of evaporation; λ, thermal conductivity of the liquid; ν, kinematic viscosity of the liquid; ρ, ρ'', densities of the liquid and the vapor, respectively; g, gravitational constant; k, Boltzmann constant; N, Avogadro number; and h, Planck's constant.

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