GENERALIZATION OF THE EXPERIMENTAL DATA ON BOILING CRISIS AT SUBMERGED SURFACES USING THE THEORY OF THERMODYNAMIC SIMILARITY

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Semiempirical equations are obtained for calculating the relative values of the maximum and minimum heat loads and the corresponding temperature differences over a wide range of pressures in the case of pool boiling.

The existing generalized formulas for the maximum and minimum specific heat fluxes q_{max} and q_{min} can be used for surfaces with a particular configuration, roughness, wettability, etc. The experimental values of q_{max} and q_{min} obtained for boiling at surfaces differing in size, cleanliness, and roughness and heated in various ways differ strongly from the calculated values and, as a rule, lie outside the limits of uncertainty of the constant coefficients in the generalized formulas. We lack reliable analytic relations for calculating q_{max} under different boiling conditions. By means of the theory of thermodynamic similarity the method of relative calculation of the maximum and minimum heat loads on the saturation line and the corresponding temperature differences can be successfully extended to any real systems.

Thermodynamic similarity was first employed by Lukomskii to calculate the thermodynamic properties of pure substances on the saturation line and for boiling heat transfer.

Subsequently, the method of generalization of the experimental data on the basis of the theory of thermodynamic similarity was used by such investigators as Rozen, Rychkov, Borishanskii, Novikov, Mostinskii, Schrock, Lienhard, etc., who obtained such useful relations as $q_{max} = f(p/p_c)$ and $q_{min} = f_1(p/p_c)$ for pool boiling. Novikov [1] and later Schrock and Lienhard [2] obtained equations for the maximum heat load relating q_{max} with the critical parameters p_c, T_c, the molecular weight, and the reduced pressure p/p_c. These relations cannot be used to generalize data for q_{max} obtained under different experimental conditions.

The method of generalization based on a broadened interpretation of the law of corresponding states, proposed by Borishanskii [3], makes it possible to compare data on the maximum heat fluxes for any surface-liquid combinations. In this case the scale of comparison is not the critical parameters, as in [1, 2], but the value of the similar quantity q^*_{max} at a selected arbitrary distance (with respect to pressure or temperature) from the critical point of the liquid-vapor system (p_*/p_c = idem or T_*/T_c = idem):

$$q_{max} = q^*_{max} F(p/p_c). \tag{1}$$

The function $F(p/p_c)$ can be determined from the experimental data in the form

$$F(p/p_c) = A(p/p_c)^m (1 - p/p_c)^n. \tag{2}$$

The coefficient A and the exponents m and n were calculated by I. L. Mostinskii [4] for $p_* = 0.03p_c$. The choice of p_* depends on the pressure range of interest. Finding the function $F(p/p_c)$ in form (2) for different p_* and the values of q_{min}, Δt_{max}, and Δt_{min} characterizing boiling crisis is of undoubted practical interest. As far as we know, there has so far been no such generalization of the experimental data for the minimum heat fluxes q_{min} and the temperature differences Δt_{max}, Δt_{min}.

Our experiments in pool boiling on the saturation line enabled us to generalize q_{min}, Δt_{max}, and Δt_{min} over a broad range of pressures, including the neighborhood of the critical point of the liquid-vapor system. The experimental apparatus was described in [5, 6]. Boiling crisis in carbon dioxide and sulfur hexafluoride [5, 7] was studied near the critical pressure ($p/p_c \simeq 0.65$–0.99) using various heaters: rounded and horizontal polished brass tubes (approx. 4 mm diam.) internally heated by a heat transfer agent, and platinum wire (approx. 29 μ diam.) heated by direct current. The boiling of n-pentane and n-hexane [6] was investigated using a horizontal copper tube (approx. 4 mm diam.) internally heated by a heat transfer agent, over a broad pressure range from atmospheric to critical. The available data of other authors, obtained under different experimental conditions, were also used in the generalization.

Figure 1 presents our data for n-pentane and n-hexane boiling on horizontal tubes [6], and the data of Morozov [8], Cichelli and Bonilla, Kazakova [9], Hoene and Huber [10] for other liquids boiling on heaters of different configuration, different size, and different surface quality. The experimental data for substances differing in their critical parameters and sharply different conditions of investigation are generalized with a spread of ±15% in $q_{max}/q^*_{max} = F_1(p/p_c)$ coordinates, where q^*_{max} is the value of the maximum specific heat load (for the corresponding substance and heater) at $p_* = 0.31p_c$. We selected this pressure because it corresponds to the greatest value of q^*_{max} and the error in determining it will be much less than at $p_* = 0.03p_c$ [3]. The equation for the maximum heat load has the form [11]

$$q_{max}/q^*_{max} = 2.1\,(p/p_c)^{0.35}\,(1 - p/p_c)^{0.9}, \quad p_* = 0{,}31\ p_c. \tag{3}$$

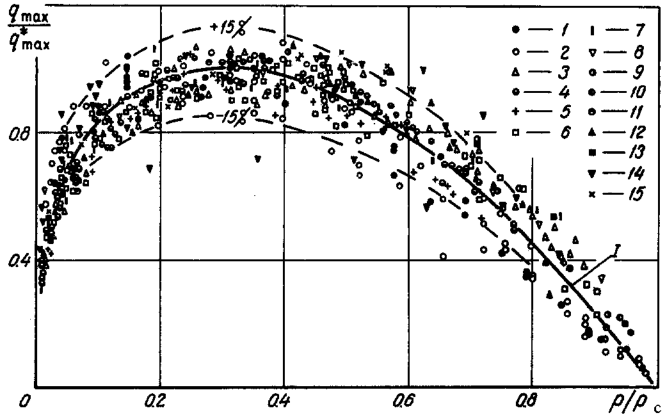

Fig. 1. Generalization of experimental data on maximum specific heat fluxes q_{max} for pool boiling ($p_* = 0.31p_c$): 1, 2) n-pentane and n-hexane (horizontal tube), authors' data; 3, 4) ethyl and methyl alcohols (horizontal plate) [8]; 5) methyl alcohol (nichrome wire) [8]; 6, 7, 8) ethyl alcohol (horizontal plate of different orientation) [8]; 9, 10, 11, 12, 13) ethyl alcohol, n-pentane, n-pentane (dirty surface), n-heptane, benzene (chrome-plated copper plate), data of Cichelli and Bonilla; 14) water (horizontal plate) [9]; 15) benzene (horizontal tube) [10]; I) from Eq. (3).

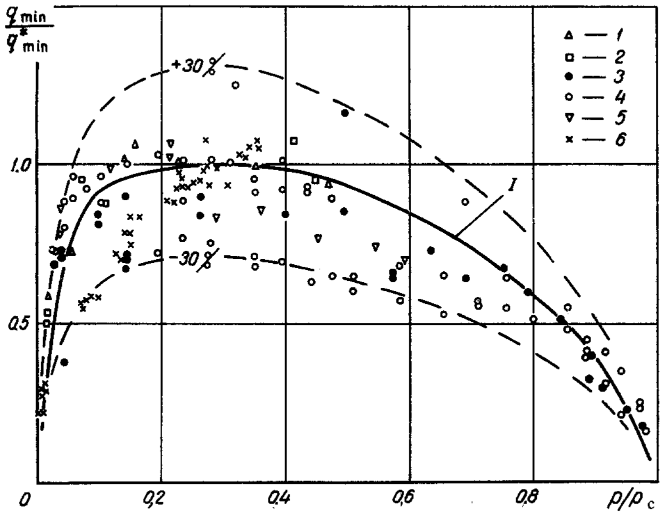

Fig. 2. Generalization of experimental data on the minimum specific heat fluxes q_{min} for pool boiling ($p_* = 0.31p_c$): 1, 2) propyl and ethyl alcohols (horizontal nichrome plate) [12]; 3, 4) n-pentane and n-hexane (horizontal tube), authors' data; 5) isooctane (horizontal rod) [13]; 6) water (nichrome wire) [14]; I) from Eq. (4).

If one of the values of the maximum heat load (q_{max} or q^*_{max}) is known, we can easily find the q_{max} for any pressure from formula (3). For the case of pool boiling on a horizontal plate one of the values of the maximum heat load can be calculated from the generalized relations of Kutateladze, Sterman, Kruzhilin, Labuntsov, Alad'ev, Borishanskii, et al. In the case of boiling on surfaces of different configuration it is most reliable to determine one of the values of q_{max} in (3) from experiment. The effect of the geometry factor, which takes into account the roughness and configuration of the heat transfer surface, the method of heating, etc., is excluded.

In Fig. 2 we have plotted our experimental data for n-pentane and n-hexane over a broad pressure range in $q_{min}/q^*_{min} = F_2(p/p_c)$ coordinates, together with the data of Morozov [12], Borishanskii [13], Petukhov and Kovalev [14] for other substances obtained under different experimental conditions ($p/p_c < 0.6$).

For $p_*/p_c = 0.31$ on the basis of (2), considering that $q_{min}/q^*_{min} = 0$ at $p/p_c = 0$ and $p/p_c = 1$, in the range $p/p_c \simeq 0-1$ correct to ±30% we have [11]

$$q_{\min}/q^*_{\min} = 1.67\,(p/p_*)^{0.24}\,(1-p/p_c)^{0.61},$$

$$p_* = 0.31\,p_c. \qquad (4)$$

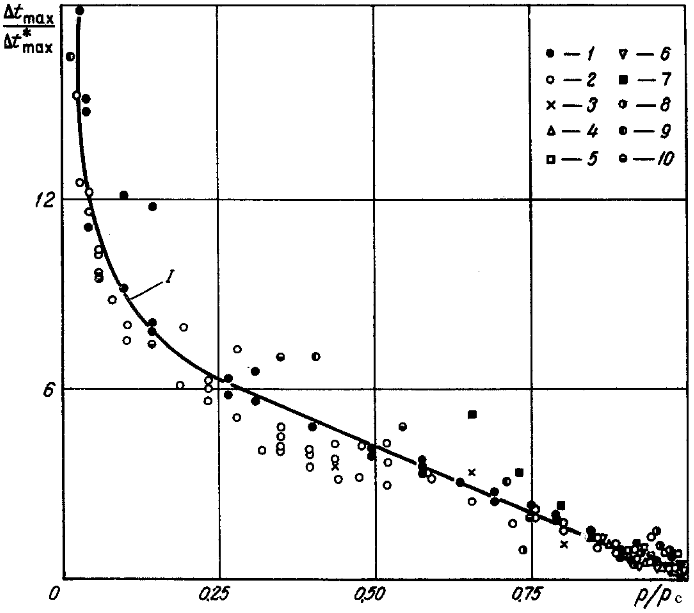

Fig. 3. Generalization of experimental data on temperature differences corresponding to maximum specific heat fluxes ($p_* = 0.9p_c$): 1, 2) n-pentane and n-hexane (horizontal tube), authors' data; 3) n-hexane (tube with wide fins), authors' data [6]; 4, 5, 6) carbon dioxide (rounded tube, platinum wire, horizontal tube), authors' data; 7) sulfur hexafluoride (horizontal tube), authors' data; 8) ethyl alcohol, inside vertical tubes [15]; 9, 10) ethyl alcohol and n-pentane (horizontal plate), data of Cichelli and Bonilla; I) from Eqs. (5) and (6).

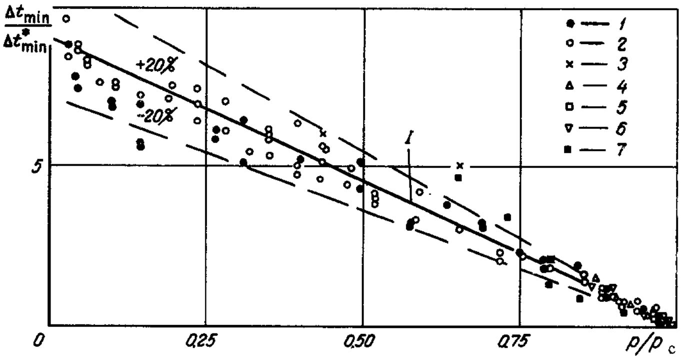

Fig. 4. Generalization of experimental data on the temperature differences corresponding to the minimum specific heat fluxes ($p_* = 0.9p_c$): I) from Eq. (7); 1–7) see Fig. 3.

The large difference in the values of $q_{\max}$ ($q_{\min}$) for different experimental conditions here is much reduced. The scatter of the experimental points is not greater than 15% (30%).

The data on the relative temperature differences corresponding to the maximum specific heat fluxes, obtained for boiling under a variety of conditions, lie close to the averaged curve (Fig. 3). The same graph includes the data of Lukomskii and Madorskaya [15] on ethyl alcohol boiling in a vertical tube at low circulation rates and the data of Cichelli and Bonilla for ethyl alcohol and n-pentane boiling on a horizontal chrome-plated copper plate. Our values of $\Delta t_{\max}$ for carbon dioxide boiling on various heaters and sulfur hexafluoride were obtained only near the critical pressure ($p/p_c > 0.6$), so that the scale value of the temperature difference $\Delta t^*_{\max}$ was taken at $p_* = 0.9p_c$. On the pressure interval up to $p/p_c = 0.3$ the dependence of $\Delta t_{\max}$ on reduced pressure takes the form

$$\Delta t_{\max} / \Delta t^*_{\max} = 3.74 (p / p_c)^{-0.38}, \; p_* = 0.9 \, p_c. \quad (5)$$

At $p > 0.3p_c$ the data are generalized by a straight line:

$$\Delta t_{\max} / \Delta t^*_{\max} = 8.42 (1 - p / p_c), \; p_* = 0.9 \, p_c. \quad (6)$$

Correct to ±20% (about 110 values were used) the temperature difference $\Delta t_{\min}$ (Fig. 4) corresponding to the cessation of film boiling is given by the equation

$$\Delta t_{\min} / \Delta t^{*}_{\min} = 9.0(1 - p/p_c), \; p_* = 0.9 \; p_c. \qquad (7)$$

One of the values of $\Delta t_{\min}$ in Eq. (7) is determined for the given pressure either by experiment or from Berenson's formula [16] for the corresponding boiling conditions.

The method of generalization of the experimental data using scale values is particularly rational and promising. It permits the comparison and calculation of $q_{\max}$, $q_{\min}$, $\Delta t_{\max}$, and $\Delta t_{\min}$ at any pressure for thermodynamically similar substances in the saturation state. Data on the specific heat fluxes and temperature differences can be obtained for cases of boiling on surfaces of different size, configuration, roughness, etc.

NOTATION

$q_{\max}$ and $q_{\min}$ are the maximum and minimum specific heat fluxes (first and second critical heat flux densities); $\Delta t_{\max}$ and $\Delta t_{\min}$ are the temperature differences corresponding to $q_{\max}$ and $q_{\min}$; $\Delta t_{\max} = t_{\max} - t_s$, $\Delta t_{\min} = t_{\min} - t_s$; $t_{\max}$ and $t_{\min}$ are the wall temperatures corresponding to the maximum and minimum of the specific heat flux along the isobar; t_s is the saturation temperature; p_c and T_c are the critical pressure and temperature; p_* is the scale pressure; $q^*_{\max}$, $q^*_{\min}$, $\Delta t^*_{\max}$, $\Delta t^*_{\min}$ are the values corresponding to scale pressure.

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