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CRITICAL THERMAL LOAD IN SATURATED BOILING OF LIQUIDS

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The critical velocity of vapor flow from the heating surface in boiling is found based on the analogy of bubbling and boiling phenomena. The relation for the critical thermal load q_{cr} is found from the assumption that this quantity corresponds to the maximum vapor velocity. The expression obtained in this work for q_{cr} describes experimental data on the saturated boiling of water, ethanol, and benzene at different pressures.

Prevention of a boiling crisis (burnout) is a necessary and sufficient condition in designing heat exchangers. This phenomenon can lead to an emergency on heat-generating devices widely used in the national economy; therefore, investigation of a boiling crisis is a topical scientific and technical problem.

According to [1], the presence of continuously varying and indefinite boundaries and of interphase exchange in boiling involves difficulties in mathematical description and makes it impossible to use direct numerical modeling. Two-phase systems are special objects whose analysis calls for consideration of the entire process. One promising line in investigation of boiling has been developed by D. A. Labuntsov [2]. He believed that one can and must reveal the main factors (whose number is small as a rule) in any, even the most complex, phenomenon. The analog method formulated by Maxwell [3] is applicable to analysis of the boiling process. This method is an apparatus giving one a comprehensive glimpse into the problem considered and enabling one to reveal the main quantities on which the critical thermal load is dependent.

In bubbling of a gas through a liquid, bubbles are deformed during the separation. The ascending velocity of bubbles u in bubbling has been analyzed by Peebles and Garber [4]. It turned out that, for deformed bubbles, this quantity is constant and independent of their size. It was found that data for 16 liquids can be described, with an accuracy to 3%, by the following formula:

$$u = 1.18 \sqrt[4]{\frac{\sigma g (\rho_1 - \rho_2)}{\rho_1^2}} . \tag{1}$$

Here u is the velocity of vapor flow through water in bubbling. This equation was first derived analytically by Frank–Kamenetskii [5]. The process of quasistatic formation of a bubble ends with its separation under gravity. It is likely that the ascending velocity of a vapor bubble near the heater surface will nearly be equal to that calculated from Eq. (1).

G. N. Kruzhilin [6] has investigated the motion of a gas through a liquid layer in steam boilers. Vapor in the form of individual bubbles and jets traverses the water layer and, disrupting the evaporation surface, arrives at the steam volume of the boiler drum. The separated droplets of the liquid rise above the evaporation surface or fall downward, or arrive at the steam line. To theoretically analyze this problem the author has used the dimensional method. It turned out that the moisture content of the gas is

$$W = AD^4 .$$

It has been found that in this case the criterion

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$$\Pi = \frac{\rho_2 \sqrt{\dfrac{\rho_2}{\rho_1}}}{g\sigma} D^4 \tag{2}$$

is the most important. This conclusion is consistent with experimental data of many authors [6] as far as the bubbling of a vapor though water and of air through kerosene is concerned. The stress of the steam volume D is directly related to the vapor velocity u, and the quantity Π has a certain constant value; therefore, the criterion (2) can be rewritten as follows:

$$\Pi = \frac{\rho_2 \sqrt{\dfrac{\rho_2}{\rho_1}}}{g\sigma} u^4 = k = \text{const} . \tag{3}$$

The velocity of motion of the vapor phase will be expressed from Eq. (3):

$$u = k \sqrt[4]{\frac{g\sigma}{\rho_2}} \sqrt[8]{\frac{\rho_1}{\rho_2}} . \tag{4}$$

Jakob and Linke [7] have found that while a bubble is still attached to the surface, its center of gravity ascends with the same velocity with which it is separated from the heating surface. This means that we have the following relations:

$$\frac{D_\text{b}}{t_\text{b}} = u . \tag{5}$$

Then the known equations $f = \dfrac{1}{t_\text{c} + t_\text{b}}$ and $D_\text{b}f$ = const and (5) yield

$$D_\text{b} f = \frac{t_\text{b}}{t_\text{c} + t_\text{b}} = u = 1.18 \sqrt[4]{\frac{\sigma g (\rho_1 - \rho_2)}{\rho_1^2}} . \tag{6}$$

The frequency of bubble emission will be maximum if the bubbles are in mutual contact, i.e., when the contact time is $t_\text{c} = 0$. The eigenfrequency of separation exists for each bubble diameter.

The product $D_\text{b} f$ is an almost universal occurrence in the analysis of bubble boiling [8]; it is constant for the nucleation site. The average values of $D_\text{b} f$ are of the same order for different liquids. Thus, Jakob and Linke [7] proposed $D_\text{b} f$ = 77 mm/sec for water, whereas Fritz and Ende [9] obtained, for the same liquid, a value of 95 mm/sec. Using the analogy of the mechanisms of bubbling and boiling [5], we also calculate the product of the separation diameter of a bubble and the frequency of its separation. Since these phenomena are similar, they are described by identical laws.

In [8, 10], it has been established from the results of experiments that the contact time is equal to the separation time. With allowance for this fact, Eq. (6) will take the form

$$D_\text{b} f = \frac{1.18}{2} \sqrt[4]{\frac{\sigma g (\rho_1 - \rho_2)}{\rho_1^2}} . \tag{7}$$

In saturated boiling at atmospheric pressure, Eq. (7) yields $D_\text{b} f$ = 93 mm/sec for water and 73 and 64 mm/sec respectively for methanol and carbon tetrachloride.

Relation (4) obtained for the velocity of motion of the vapor phase in bubbling can be applied to investigation of boiling. It is analogous to Eq. (5); therefore, we write

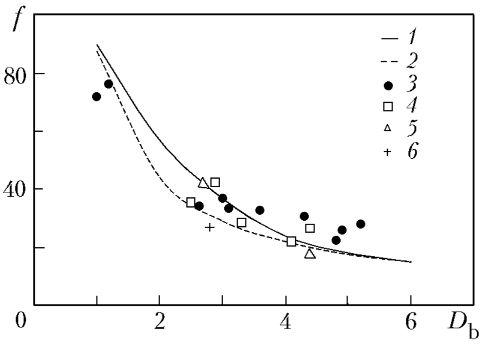

Fig. 1. Frequency of emission of bubbles separated from a horizontal surface vs. their diameter in boiling of different liquids: 1) calculation from (7) for water; 2) calculation from (8) for water; 3) experimental data [9] for water; 4) data [11] for water; 5) experiments [7] for carbon tetrachloride; 6) data [12] for methanol. D_b, nm; f, sec^{-1}.

$$u = D_b f = k \sqrt[4]{\frac{g\sigma}{\rho_2}} \sqrt[8]{\frac{\rho_1}{\rho_2}} . \qquad (8)$$

Here $k = 1$ and u is the velocity of motion of the vapor phase from the heating surface in boiling of the liquid. Calculation from Eq. (8) for water in saturated boiling at one atmosphere yields $D_b f = 85$ mm/sec.

Figure 1 plots the frequency of emission of bubbles as a function of the diameter of a bubble separated from a horizontal surface. Experimental data collected by several authors in boiling of different liquids are compared to those calculated from formulas (7) and (8) for water. These formulas are seen to satisfactorily describe experiment.

From 6 to 12 nucleation sites were thoroughly investigated in [12] and diameters by the instant of separation were measured. It has turned out that the average bubble diameter and the average separation frequency are invariable for heat fluxes of nearly 80% of the critical value. For thermal loads close to the critical values, the bubbles coalesce and jet boiling is observed [13]; therefore, these quantities are difficult to calculate. In the range of constant values of the diameter and the frequency, their product is a constant of 102 mm/sec for methanol. Jakob and Linke [7] have obtained $D_b f = 79$ mm/sec for water in the case of small heat fluxes. The constancy of the bubble size and separation frequency (with growth in the thermal load to 80% of its critical value) means that the enhancement of the heat flux with temperature head must only produce the corresponding increase in the number of nucleation sites. But from the instant when the specific heat flux amounts to 80% of the critical value, the growth in the number of nucleation sites is retarded.

Thus, we see that the similarity of the bubbling and boiling processes is confirmed, among other things, by the fact that these phenomena are described by identical laws; therefore, this analogy can be applied to description not only of the separation diameter and separation frequency of vapor bubbles but the critical thermal load as well.

Change in the flow regimes in bubbling of a gas through a liquid layer leads to the following phenomenon. It has turned out that there is a certain limiting gas velocity above which gas jets cease to move stably in the liquid. This upper limit is called the "immersion" or "submersion" point [14]. For this process the value of the "submersion" velocity is determined by both the velocity of the gas moving from the surface and the velocity of the liquid heading for the surface. If we are assigned any gas velocity, there is quite a definite liquid velocity above which the filled gas jet will be submerged.

The mechanism of the submersion (flooding) phenomenon in bubbling has been described in [15] in detail. It occurs in any device in which one liquid flows discontinuously through the second, immiscible, liquid. The dispersed phase, traversing the continuous phase, has a smaller velocity than that at entry. The velocities of the media flowing in opposition are independent; therefore, submersion occurs with their rapid synchronous increase; we can have one of the two cases. The first case: the traversal of the continuous phase is delayed, and the dispersed phase gives a reverse motion; the second case: a short delay in the motion of any of the media becomes sufficient for the second to fill the volume available in the vessel; one of the phases is discharged more or less strongly from the apparatus.

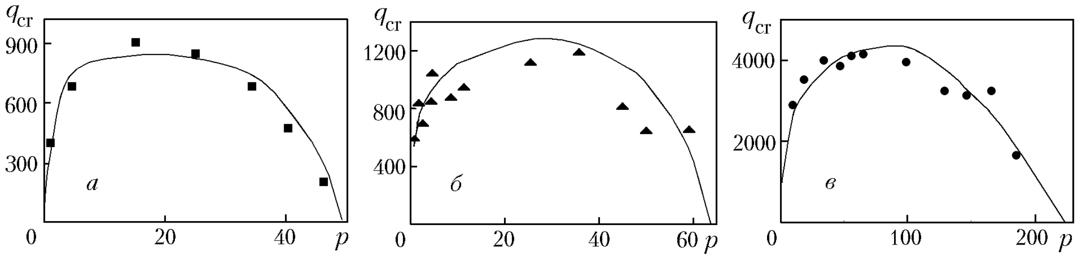

Fig. 2. Critical thermal load q_{cr} in saturated boiling of benzene (a), ethanol (b), and water (c) as a function of the pressure p; curves, calculation from (11); points, experimental data of [6] (a), [17] (b), and [18] (c). p, bar; q_{cr}, kW/m^2.

Thus, submersion in bubbling occurs when the liquid and gas counterflows attain such velocities for which the liquid and the gas begin to compete for the free volume. Photographic investigation of boiling has shown [13] that for near-critical thermal loads, vapor jets move from the heating surface, whereas the liquid flows in the opposite direction — to the heating surface. Boiling crisis begins if more vapor is formed on the heat-exchange surface compared to its amount that can be transferred by stable vapor jets.

Boiling crisis is a hydrodynamic phenomenon that can be interpreted analogously to the phenomenon of submersion. The critical thermal load is attained when the vapor-phase velocity reaches its maximum (critical) value [14]. Similarly to the experiments of [16], the liquid will be thrown from the heating surface, i.e., pressing of the liquid by the vapor will occur.

In considering the problem on the moisture content of the vapor in bubbling in steam boilers, G. N. Kruzhilin has inferred that, from Eq. (2), one can find the pressure dependence of the permissible (critical) load of the steam volume in the case of the traversal of the free volume by the vapor. Under bubbling-flooding conditions corresponding to a boiling crisis, the moisture content of the vapor attains quite a definite (critical) value; therefore, expression (3) can be rewritten in the form

$$\frac{\rho_2\sqrt{\frac{\rho_2}{\rho_1}}}{g\sigma}\,u_{cr}^4 = \text{const}\,. \qquad (9)$$

Thus we obtain the "fourth-degree formula" (important in boiling-crisis theory) for the velocity of motion of the vapor phase.

From a consideration of the development of the boiling and bubbling processes, the mechanisms of boiling crisis and flooding in bubbling are identical, which is confirmed, in particular, by our calculation of the frequency of separation of vapor bubbles from formula (8). Then, from Eq. (9), we obtain an expression for the velocity of motion of the vapor phase:

$$u_{cr} = \frac{q_{cr}}{\rho_2 L} = \Pi_1 \frac{\sqrt[4]{g\sigma}}{\sqrt[4]{\rho_2}\sqrt[8]{\frac{\rho_2}{\rho_1}}}\,. \qquad (10)$$

Expression (10) can be rewritten for the critical thermal load as

$$q_{cr} = \Pi_1 L\,(\rho_2)^{5/8}\,\sqrt[4]{g\sigma}\,\sqrt[8]{\rho_1}\,. \qquad (11)$$

Figure 2 compares results of calculation of the critical thermal load q_{cr} from formula (11) and experimental data obtained by different authors in a wide pressure range in boiling of benzene, ethanol, and water. The constant Π_1 turns out to be equal to 0.2–0.3. It is seen that the agreement of the calculated data and experiment is satisfactory in a wide pressure range. Using of the analogy of the bubbling and boiling processes in describing their characteristics is thus justified.

CONCLUSIONS

1. The similarity of the processes of bubbling and boiling is confirmed by the fact that these phenomena are described by identical laws. Thus, the velocity of motion of the vapor phase through a perforated sheet in bubbling and from the heating surface in boiling can be calculated from formulas (4) and (8).

2. The theoretical relation for determination of the frequency of separation of vapor bubbles as a function of the bubble diameter (formula (8)) has been obtained. The coincidence of the results of calculation from (8) with experimental data is satisfactorily.

3. The application of the analog method to bubbling and boiling processes enables one to obtain a theoretical relation for the critical thermal load in a wide pressure range for different organic liquids and water.

NOTATION

A, Π, Π_1, and k, constant values; D, stress of the steam volume in bubbling, $m^3/(m^3 \cdot sec)$; D_b, separation diameter of a bubble, m; f, frequency of separation of vapor bubbles, 1/sec; g, free-fall acceleration, m/sec^2; L, heat of vaporization, J/kg; q_{cr}, critical thermal load, kW/m^2; t_c, contact time, i.e., time interval necessary for superheating the liquid, sec; t_b, time necessary for attaining diameter D_b by the bubble, sec; u, velocity of motion of the vapor, m/sec; u_{cr}, critical velocity of motion of the vapor, m/sec; W, moisture content of the vapor, %; ρ_1, density of the liquid, kg/m^2; ρ_2, density of the vapor, kg/m^2; σ, surface tension of the liquid, N/m. Subscripts: 1, liquid; 2, vapor; cr, critical; b, bubble; c, contact.

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