CRITICAL HEAT FLUXES IN THE POOL BOILING OF LIQUIDS AT REDUCED PRESSURE

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The authors report the results of a study of the critical heat fluxes and boiling mechanism of certain liquids at reduced pressures.

As a result of experiments to determine the critical heat fluxes in the pressure range 0.05–1 bar during boiling of distilled water, ethanol and benzene on horizontal heaters of various diameters (from 0.2 to 5.0 mm) it has been found that at pressures $p \leq 0.2$–0.3 bar for water and ethanol the hydrodynamic stability criterion

$$k = q_* / r\sqrt{g\gamma''}\,\sqrt[4]{\sigma(\gamma' - \gamma'')}$$

is not constant but depends on pressure [1]. Figure 1 gives the results of the experiments in the form of a relation between the stability criterion k and the complex Δ, characterizing the influence of the transverse dimension of the heater, for pressures $p = 1.0$, 0.2, and 0.1 bar (curves 1, 2, 3). It is clear from the graph that for horizontal cylindrical heaters there are three regions of influence of the geometric heater dimension on the critical heat flux q_*. In the region $0.2 < \Delta < 1.0$ there is a maximum of the critical heat flux density, at $\Delta < 0.2$ the value of q_* falls sharply, and when $\Delta > 1.6$ we get self-similarity of q_* relative to the linear dimension. A similar relation was previously obtained in [2] for atmospheric pressure and above. The nature of the relationship between k and Δ is also preserved under vacuum conditions; however, starting from a pressure $p \approx 0.2$ bar for water and ethanol, there is a certain increase in the stability criterion in the self-similarity region ($\Delta > 1.6$) and a more substantial increase in k in the region of thin heaters. At $p \approx 0.1$ bar there is a more important increase in k; thus, in the self-similarity region the value of k increased from 0.15 to 0.18, while in the thin heater region the increase was from 0.20 to 0.28. For benzene at a pressure $p \approx 0.2$ bar there is a small increase in k (by about 10%) in the self-similarity region, and no change is observed for boiling on thin heaters (experiments with benzene were not performed at pressures below 0.2 bar).

The increase of k in the low-pressure region is confirmed by the data of Van Stralen [3] and Schrok and Lienhard [4] on the critical heat fluxes for water boiling on wires 0.2 and 0.5 mm in diameter. According to the data of [4], at pressures $p \leq 0.3$–0.2 bar k increases by about 25% and, according to the data of [3], by 40%, while at the lowest pressures obtained in those experiments $p \approx 0.02$–0.03 bar k increases by a factor of 2 as compared with the data for atmospheric pressure. The lowest pressure in the experiments with boiling benzene in [4] was 0.25 bar, and in that case an increase in k was not observed.

It may be assumed that the increase in the stability criterion at low pressures is associated with the special characteristics of the boiling mechanism under those conditions.

We made a number of films of the boiling process for the above mentioned liquids at film speeds of 750–2000 frames/sec and at different pressures and heat fluxes.

The data obtained after analyzing the high-speed films for the breakaway diameter D_0 and the mean rate of growth of vapor bubbles on the surface, computed as $w_0'' = D_0/\tau''$, are given in a table (p. 89). It follows from the data that with decrease in pressure D_0 and w_0'' increase. Thus, at $p = 0.1$ bar w_0'' for water and ethanol increases by about three times as compared with atmospheric pressure.

Figure 2 presents growth curves for three bubbles in water boiling on an insulated plate 9 mm wide in the form of the relation $D_0 = f(\tau'')$ and, for comparison, lines representing the results of calculations based on the Zuber-Forster formula [5]

$$D_0 = 2\sqrt{\pi}\,\frac{c\Delta T\gamma'}{r\gamma''}\sqrt{a\tau''} \tag{1}$$

and the Labuntsov formula [6]

$$D_0 = 2\sqrt{2\beta\frac{c\Delta T\gamma'}{r\gamma''}a\tau''}. \tag{2}$$

It is clear from the experimental curves that the bubbles grow at different rates; in the initial period $\tau'' < 3 \cdot 10^{-3}$ sec the growth rate is greatest, the exponent h of τ'' reaches 1 or more. Then the growth rate slows down, and in the final stage the bubbles grow roughly at the same rate, with $h \approx 0.5$. This type of bubble growth at pressures near atmospheric has been noted in a number of studies [7, 8]. Figure 3 shows a series of photographs illustrating bubble growth for water boiling on an insulated plate. The size of the bubble at the moment of separation is 25 mm, the time interval between frames is 0.008 sec. At the very beginning of growth the bubble is hemispherical, then it is pulled out in the vertical direction acquiring an almost spherical shape. In order to construct the growth curves we measured the height of the bubble at definite time intervals. As shown in Fig. 2, calculation of the breakaway diameter from Eq. (1) gives results that are almost four times too high, while the calculated dimension of the bubble before breakaway based on formula (2) is 1.8 times lower than that obtained experimentally. A comparison of the experimental values of D_0 with those calculated from formulas (1) and (2) for water and ethanol under the various conditions indicated in the table showed that the calculated values of the breakaway diameter based on formula (1) are several times greater than the experimental values, the discrepancy increasing with decrease in pressure. Thus, at $p = 0.1$ bar the calculated value of D_0 is five times greater than the experimental value. Calculations based on formula (2) give close agreement with experiment at pressures near atmospheric ($p = 0.5$–1.0 bar), but at pressures $p = 0.06$–0.15 bar the calculated values of D_0 are about half the experimental values.

If it is assumed that the increase in k at low pressures is associated with an increase in the growth rate of vapor bubbles on the heating surface (i.e., with the more rapid removal of vapor from the heating surface), we may introduce the Froude number in the form

$$\mathrm{Fr} = \frac{w_0''^2}{g}\sqrt{\frac{\gamma' - \gamma''}{\sigma}} \qquad (3)$$

and analyze the experimental critical heat flux data in the coordinates

$$k/k_0 = f\left(\frac{w_0''^2}{g}\sqrt{\frac{\gamma' - \gamma''}{\sigma}}\right), \qquad (4)$$

where k_0 is the stability criterion for the given liquid in the region of self-similarity with respect to the Fr number defined as in (3). The results of such analysis of our data are presented in Fig. 4.

Clearly, the stability criterion remains constant at Froude numbers less than 8, while at greater values it begins to increase.

This relationship between k and Fr was constructed for the region of self-similarity with respect to Δ, since the data on the bubble growth rate at the heating surface relate to heaters 2 and 3.2 mm in diameter and to insulated plates 5–9 mm wide.

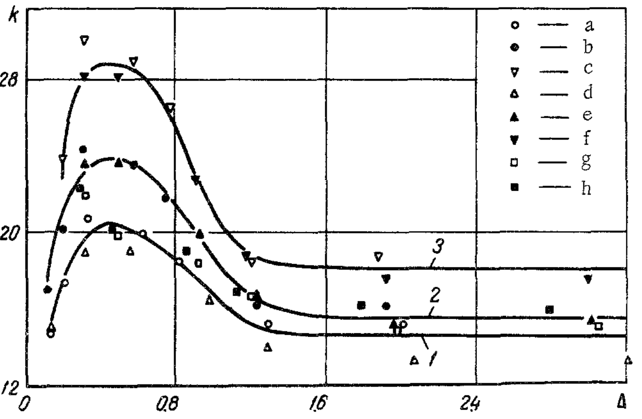

Fig. 1. Stability criterion k as a function of the parameter Δ for boiling water, alcohol, and benzene: a, b, c) water, p = 1.0, 0.2, and 0.1 bar; d, e, f) alcohol, p = 1.0, 0.2, and 0.1; g, h) benzene, p = 1.0 and 0.2.

It should also be noted that the values of the mean velocities w_0'', substituted in the Froude number, were determined for heat fluxes when individual isolated bubbles are formed. However, in some experiments at large heat fluxes, when the bubbles are already beginning to interact, bubbles that had not run together were selected. It is not possible to determine the growth rate under near-critical conditions owing to the extremely complicated and unstable hydrodynamics of the two-phase boundary layer. Whereas at pressures above atmospheric, bubbles that have run together have an almost spherical shape and data on this type of bubble at large heat fluxes can be analyzed in the usual way [9], at low pressures owing to interaction of the bubbles highly deformed vapor formations developed. At low pressure and large heat fluxes the vapor bubbles come into contact with each other before they reach their breakaway diameter; thus the bubbles interact both with neighboring bubbles on the surface and in the body of the liquid with bubbles that have previously broken away.

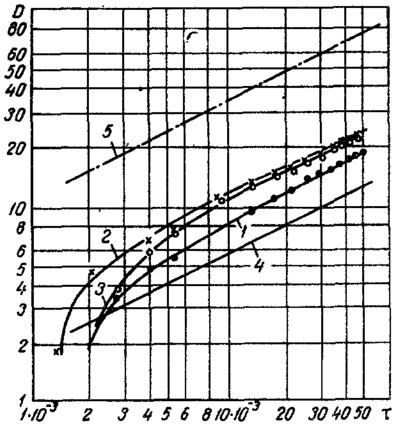

Fig. 2. Comparison of experimental data on bubble growth for water with equations (1) and (2) at $p = 0.18$ bar, $q = 0.8 \cdot 10^5$ W/m² (D_0 in mm, τ'' in sec): 1, 2, 3) experimental data; 4, 5) calculations based on formulas (2) and (1).

With decrease in pressure the critical dimension of the vapor phase nuclei, given by the expression

$$R_{\min} = 2\sigma T'' A / r\gamma'' \Delta T, \qquad (5)$$

increases several times. Thus, at a pressure $p = 0.1$ bar for ethanol and water, $R_{\min}$ increases by about four times as compared with the value at $p = 1.0$ bar.

The adopted method of analyzing the experimental data is justified to some extent in that, as already pointed out, the maximum bubble growth rate occurs in the initial period. Therefore the high growth rates at low pressures measured for individual bubbles are also characteristic of the bubbles that occur at near-critical heat fluxes. However, the mean rate w_0'' introduced into the Froude number should be regarded as a certain scale.

Thus, for the first time relation (4) links data on the mechanism of formation of individual bubbles with one of the basic integral characteristics of the boiling process (stability criterion).

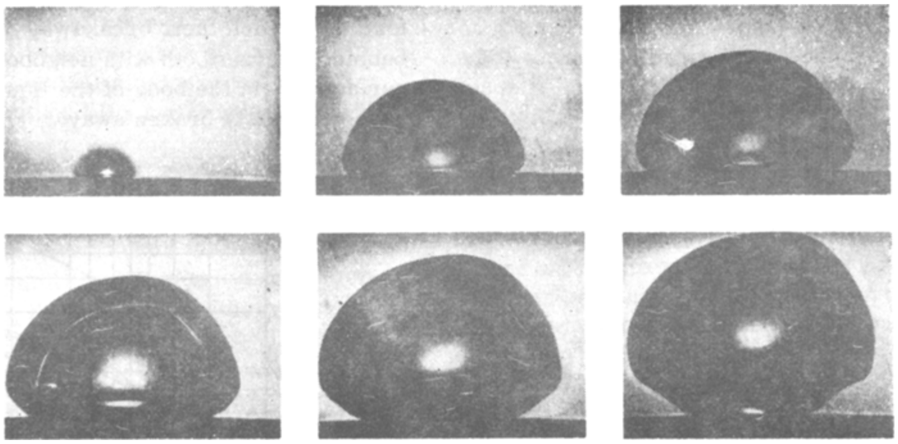

Fig. 3. Growth of vapor bubble on insulated plate ($p = 0.18$ bar, $q = 0.8 \cdot 10^5$ W/m^2).

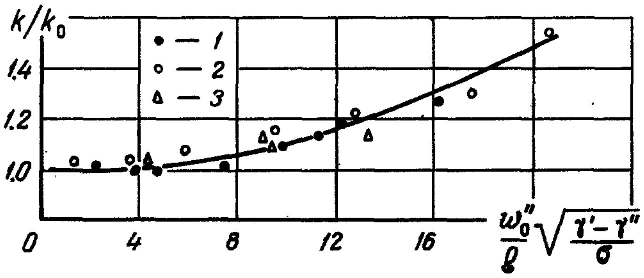

Fig. 4. Stability criterion as a function of the Froude number for water (1), alcohol (2), and benzene (3).

Results of Film Analysis

p, bar	q, W/m^2	D_0, mm	w''_0, cm/sec	$Fr = \frac{w_0''^2}{g}\sqrt{\frac{\gamma' - \gamma''}{\sigma}}$	k	k/k_0
Water						
0.095	$1.6 \cdot 10^5$	32.0	64.0	16.10	0.194	1.275
«	$2.3 \cdot 10^5$	33.3	66.0			
0.120	$2.8 \cdot 10^5$	27.0	56.0	12.20	0.181	1.19
0.150	$1.0 \cdot 10^5$	26.0	53.0	11.20	0.172	1.13
«	$2.0 \cdot 10^5$	22.5	51.0			
»	$3.85 \cdot 10^5$	25.0	58.0			
0.18	$0.8 \cdot 10^5$	18.0	47.5	9.85	0.166	1.09
»	$1.6 \cdot 10^5$	18.5	49.0			
»	$3.3 \cdot 10^5$	20.5	55.0			
0.30	$0.8 \cdot 10^5$	15.0	43.0	7.27	0.154	1.01
0.50	$0.8 \cdot 10^5$	6.8	33.0	4.70	0.150	0.99
»	$1.6 \cdot 10^5$	10.0	35.5			
0.65	$0.8 \cdot 10^5$	4.6	31.0	3.82	0.151	0.995
1.01	$0.8 \cdot 10^5$	2.5	23.0	2.16	0.152	1.0
Ethanol						
0.06	$0.6 \cdot 10^5$	28.5	59.5	20.85	0.206	1.53
»	$1.2 \cdot 10^5$	27.0	59.0			
0.10	$0.6 \cdot 10^5$	21.4	51.5	16.1	0.175	1.30
0.15	$0.3 \cdot 10^5$	18.0	45.5	12.80	0.163	1.22
»	$0.6 \cdot 10^5$	15.0	44.0			
»	$1.2 \cdot 10^5$	17.0	48.0			
0.18	$0.75 \cdot 10^5$	9.7	39.0	9.5	0.155	1.15
»	$1.4 \cdot 10^5$	9.6	40.0			
0.31	$0.6 \cdot 10^5$	6.3	30.5	5.80	0.143	1.06
0.43	$0.3 \cdot 10^5$	3.2	24.0	3.67	0.138	1.03
1.01	$0.3 \cdot 10^5$	1.1	14.5	1.37	0.134	1.0
Benzene						
0.160	$4.3 \cdot 10^4$	15.0	48.0	13.25	0.169	1.13
0.173	$6.8 \cdot 10^4$	13.0	40.0	9.0	0.167	1.11
0.204	$4.3 \cdot 10^4$	10.5	40.5	9.41	0.163	1.09
0.375	$3.0 \cdot 10^4$	3.5	27.0	4.35	0.155	1.03

NOTATION

A is the thermal equivalent of work; g is the acceleration of gravity; σ is the surface tension; γ', γ'' are the specific weights of water and vapor; r is the latent heat of vaporization; a is the thermal diffusivity; c is the specific heat; $\beta = 10$ is a constant; q_* is the critical heat flux; T'' is the absolute temperature of saturated vapor; T_w is the temperature of the heating surface; $\Delta T = T_w - T''$ is the temperature difference at the heating surface; D is the heater diameter; D_0 is the vapor bubble breakaway diameter; τ'' is the time of vapor bubble growth on the heating surface; $w_0'' = D_0/\tau''$ is the mean rate of growth of the vapor bubble on heating surface; $\Delta = D/(\sigma/(\gamma' - \gamma''))^{1/2}$ is the dimensionless complex taking into account the effect of heater diameter.

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