INTERNAL CHARACTERISTICS OF HYDROGEN BOILING

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Study of the internal characteristics of boiling is of great importance in understanding the physics of this complex process; data on internal characteristics may be used for derivation of formulas for integral boiling characteristics (heat-liberation coefficients, critical thermal flux densities). Only a limited number of works have been dedicated to study of boiling of cryogenic liquids over a wide saturation pressure range. In [1] the internal characteristics of nitrogen boiling were studied at pressures from 0.1 to 8 bar, while oxygen was studied from 0.22 to 2 bar. In [2] detachment radius and bubble-detachment frequency were determined for hydrogen boiling over the pressure range 1-11 bar. The present study is dedicated to an examination of internal characteristics of hydrogen boiling over the saturation pressure range from triple point pressure (0.072 bar) to 2.0 bar.

The experimental method and apparatus used were described in [3]. The hydrogen boiling experiments were performed with horizontal tubular German silver heaters 3.1 and 5 mm in diameter, 80 and 88 mm long, respectively. Heater surfaces were finished to class 7-8 of GOST (All-Union State Standard) 2789-73.

The temperature of the heat-liberating surface, with appropriate consideration of wall thermal resistance, was determined by a low inertia platinum resistance thermometer located inside the helium filled tubular heater.

Cine photography of the boiling process was performed with an SKS-1M high-speed camera and "Jupiter-6" telephoto lens, using 04-180 cine reversal film at an average frame rate of about 3500 frames/sec. The cine frames were processed with 15-20-fold magnification projection. Bubbles growing in isolation on the upper edge of the heater were selected for processing.

TABLE 1

Heater diameter, mm	Exp. No.	p, bar	ΔT, K	q, W/m²
3,1	1	0,072	4,35	3000
	2	0,126	3,35	2380
	3	0,342	1,85	585
	4	0,62	1,20	325
	5	0,72	1,05	330
	6	1,00	1,15	400
5,0	7	0,072	3,80	4500
	8	0,08	2,60	1150
	9	0,134	3,90	2500
	10	0,138	1,20	500
	11	0.20	3,20	2260
	12	0,535	0,90	290
	13	0,69	0,80	260
	14	0,82	0,26	180
	15	1,0	0,60	200
	16	1,3	0,40	120
	17	1.5	0,75	260
	18	2,0	0,40	310

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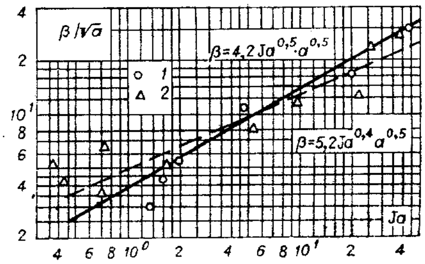

Fig. 1

TABLE 2

Exp. No.	No. of measurements	n	$\beta(n)$, cm/sec	δ_β, %	$\beta(0.5)$ cm/sec	δ_β, %	τ_d, μsec	σ_{τ_d}, ±μsec
1	9	0,65	3,50	±23	1,55	±15	9,5	2,2
2	11	0,51	0,75	±11	0,73	±13	10,1	2,7
3	24	0,46	0,34	±3	0,43	±11	10,9	1,1
4	27	0,43	0,25	±3	0,24	±12	13,8	2,4
5	16	0,4	0,12	±4	0,19	±15	13,5	1,9
7	10	0,5	1,24	±12	1,31	±12	9,3	2,4
8	10	0,46	0,93	±8	1,12	±10	9,5	1,7
10	15	0,35	0,20	±6	0,38	±16	16,5	1,9
12	23	0,39	0,15	±4	0,23	±12	20,1	3,0
15	12	0,39	0,2	±6	0,21	±13	14,2	2,5

Vapor Bubble Growth on Heater Surface

Parameters at which the study of internal boiling characteristics was performed are presented in Table 1.

The mean bubble diameter was calculated as the arithmetic mean of its vertical h_1 and horizontal h_2 dimensions, $\langle D \rangle = 0.5(h_1 + h_2)$. The bubble form remained practically spherical over the pressure interval 0.072–0.6 bar, while at pressures above 0.6 bar, at the moment of detachment the bubbles elongate and the vertical dimension increases, sometimes reaching a value of $2h_2$.

The experimentally determined dependence of bubble radius on time may be represented by the form

$$R = \beta(n)\tau^n. \tag{1}$$

Values of $\beta(n)$ and n were determined by the method of least squares for each of the experiments from the entire set of experimental data on bubble growth. The relative error in measurement of δ_β is presented in Table 2 where a general tendency to an increase in exponent n with increase in pressure is evident (with the exception of the point p = 0.138 bar).

The differing values of n indicate different values of the growth modulus $\beta(n)$, cm/sec. In order to compare the experimental data on bubble growth at various pressures the experimental growth curves were approximated by the theoretical function [4]

$$R = \beta(0.5)\tau^{0.5}. \tag{2}$$

Over the time interval from bubble generation to detachment such bubble growth curves differ from the experimental ones by no more than 25% because of the small difference of the experimental n values from the theoretical n = 0.5. The mean values of $\beta(0.5)$ obtained in this manner for each of the experiments are presented in Table 2.

The well-known theoretical relationships for the bubble-growth modulus $\beta(0.5)$ may be written in the form [4]

$$\beta(0.5) = C_\beta \mathrm{Ja}^{n_\beta} a^{1/2}, \tag{3}$$

where $n_\beta = 0.5$–1; C_β is a constant (in some studies, a function of the physical properties of the liquid and heater material [5]); $\mathrm{Ja} = \lambda\Delta T / L\rho'' a$ is the Jacobs number; λ, a are the coefficients of thermal conductivity

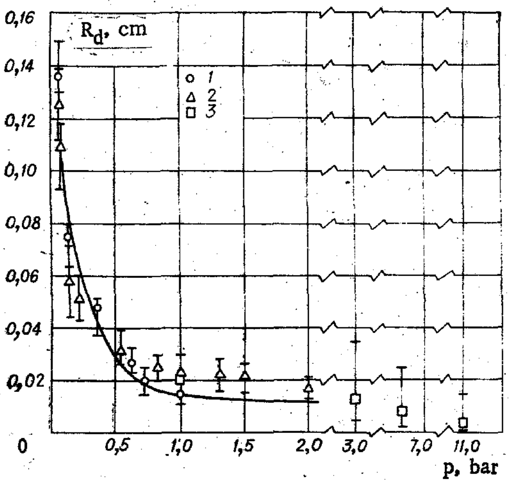

Fig. 2

and diffusivity of the liquid; L is the latent heat of vaporization; ρ'' is the vapor density; and ΔT is the temperature head.

To determine the experimental value of n_β in Eq. (3) for the case of hydrogen boiling the dependence of $\beta(0.5)/\sqrt{a}$ on the Jacobs number was determined. Processing of all experimental data on $\beta(0.5)$ presented in Table 2 by the method of least squares gives the following expression for the vapor bubble-growth modulus in hydrogen boiling:

$$\beta(0.5) = 5.2\mathrm{Ja}^{0.4}a^{0.5}. \tag{4}$$

To approximately the same accuracy the experimental data are described by an expression close to the theoretical one of [4],

$$\beta(0.5) = 4.2\mathrm{Ja}^{0.5}a^{0.5}. \tag{5}$$

Equation (4) practically coincides with Labuntsov's formula [4], in which n_β + 0.5; $C_\beta = \sqrt{12}-\sqrt{20}$.

Figure 1 presents Eqs. (4), (5) in the form of the function $\beta(0.5)/\sqrt{a} = f\,(\mathrm{Ja})$, together with mean corrected experimental values of the growth modulus $\beta(0.5)$, obtained in two series of experiments [1) with 3.1 mm diameter heaters; 2) with 5 mm diameter heaters]. The large scattering of the experimental data at low Jacobs number (Ja $\le$ 1) is explained primarily by the low accuracy in determination of bubble diameters and temperature heads in the relatively high saturation pressure range. It is evident from Fig. 1 that for Ja > 1.6, Eq. (4) describes the experimental data better than Eq. (3).

Characteristics of Vapor Bubble Detachment

Experimentally determined values of vapor bubble-detachment radius R_d for hydrogen boiling in the saturation pressure range studied, obtained with heaters (1 – 3.1 mm diameter; 2 – 5 mm diamter; 3 – averaged results of [2]), are presented in Fig. 2. It is evident that just as in nitrogen, oxygen, water, and organic liquid boiling [1, 6], bubble-detachment radius increases with increase in pressure, and this dependence becomes especially great at sufficiently low pressures (p < 0.5 bar).

The method of estimating R_d values proposed by one of the authors of [1, 7] was used for quantitative interpretation of the experimental data. The calculated dependence of R_d on p presented in Fig. 2 is of the same character as the experimental one and agrees with the latter satisfactorily.

The value of R_d for boiling at sufficiently low pressures (for example, $p < 0.005p_*$, where p_* is the critical pressure) and at sufficiently high pressures (for example $p > 0.05p_*$) may be described by the simple functions of [7]:

a) for low pressure (dynamic bubble-detachment regime)

$$R_d = C_R\,\beta^{4/3}g^{-1/3}; \tag{6}$$

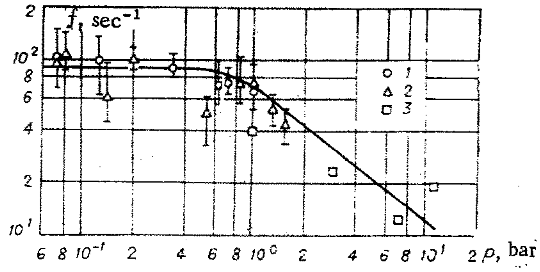

Fig. 3

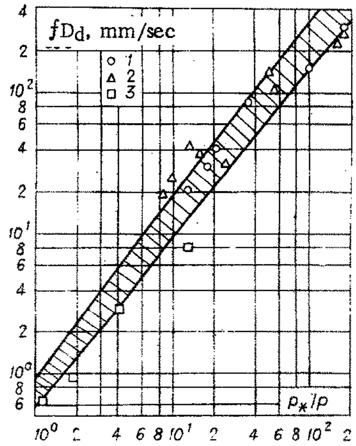

Fig. 4

b) for high pressure (quasistatic bubble-detachment regime)

$$R_d = \sqrt[3]{(3/2)R_c\sigma/g(\rho - \rho'')}, \tag{7}$$

where C_R is a constant coefficient of the order of unity ($C_R \approx 1.34$ [7]); g is the acceleration of gravity; and σ is the surface tension.

Equation (7) is an analog of the well-known Fritz formula [8] for the case of boiling of liquids with very small boundary angles (including cryogenic liquids), where the Fritz formula is inapplicable [7, 9], and bubble detachment must take place not from a smooth heater surface, but from the edge of a microcavity of radius R_c in which the vapor bubble is generated. The value of R_c is defined according to [10] as the diameter of a critical vapor nucleus under the given experimental conditions. The growth modulus β for construction of the theoretical function is calculated from Eq. (5) for Ja > 1.6 and from Eq. (4) for Ja < 1.6.

Calculation of the forces acting on the hydrogen vapor bubble upon detachment, using the method of [7], reveals that dynamic forces (inertial forces of liquid reaction and frontal resistance) exceed static forces (surface tension) at $p \leq 0.4$ bar or $p \leq 0.03p_*$. This pressure is close to the value at which an inflection occurs in the function $R_d = f(p)$ for both hydrogen (Fig. 2) and a number of liquids of widely differing thermodynamic properties (nitrogen, oxygen, water, Freon-12), for which the corresponding pressure boundary is about $0.02p_*$ [1]. It can be seen that bubble dimensions in the dynamic detachment regime described by Eq. (6) must hange more rapidly with pressure than in the static regime where dimensions are described by Eq. (7) or the Fritz equation [Eq. (8)].

We note that there exists not only qualitative analogy, but quantitative agreement of the generalized results on internal boiling characteristics of high-boiling-point liquids (water, ethanol) with those for cryogenic liquids (hydrogen) at sufficiently low saturation pressures. In [8] results were presented of water, ethanol, and benzene boiling in the form of dimensionless diameter $D_d\sqrt{g(\rho-\rho'')/\sigma}$ as a function of Froude number Fr = $(D_d^2/\tau_d^2 g)\sqrt{g(\rho-\rho'')/\sigma}$. This empirical relationship may be written with satisfactory accuracy in the form

$$D_d = 4/3\tau_d^2 g. \tag{8}$$

It can be shown that Eq. (8) may be obtained by substitution of Eqs. (1), (2) at $\tau = \tau_d$ in Eq. (5) with the value $C_R \approx 1.15$, which differs from the theoretical value of [7] by only 14%.

Values of bubble-growth time on the heater τ_d as a function of pressure are presented in Table 2, where $\sigma_{\tau d}$ is the mean square error of the measurement. Expectancy time τ_W (from moment of bubble detachment until moment of appearance of new bubble) was absent at all pressure values ($\tau_W \approx 0$). At the very lowest pressure, corresponding to the triple point, boiling was unstable. Bubbles detached in series within which $\tau_W \approx 0$, while time intervals between series were irregular.

Figure 3 presents vapor bubble-detachment frequency $f = \tau_d^{-1}$ as a function of pressure from experimental results obtained with two heaters: 1) heater diameter 3.1 mm; 2) 5 mm; 3) averaged results of [2].

Despite the conditional nature of this function and the high scattering of experimental points, one can reliably distinguish two pressure regions with different rules for bubble-detachment frequency: 1) a region where f is practically independent of p (p = 0.072-0.8 bar); 2) a region where f decreases sharply with increase in p (p > 0.8 bar or p > $0.05p_*$). The latter region corresponds to the quasistatic detachment regime, and its limit is the same as in other liquids [1].

Figure 4 shows mean bubble-growth rate $D_d f$ for hydrogen boiling (1 — 3.1-mm-diameter heater; 2 — 5-mm-diameter heater; 3 — data of [2]) as a function of the parameter $\Pi = p_*/p$. The crosshatched region of Fig. 4 corresponds to data for organic liquids [11]. Thus, the tendency for change in value of $D_d f$ with change in pressure in a cryogenic liquid (hydrogen) is the same as in organic liquids, while the numerical values of $D_d f$ in these two different classes of liquid coincide within the limits of experimental error.

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