EFFECT OF PRESSURE ON INTERNAL CHARACTERISTICS OF NITROGEN AND OXYGEN BOILING

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The pressure dependence of the internal characteristics of nitrogen and oxygen boiling is investigated. Formulas are derived for the break-off radii and the growth module of the vapor bubbles.

The interest in boiling of cryogenic liquids is constantly increasing due to their ever increasing use in different fields of science and technology. In recent years a number of articles have appeared that are devoted to the experimental investigation of the boiling characteristics required for engineering computations (heat-transfer coefficients and critical densities of the heat flux) in a wide range of pressures [1-4]. However, the data on the internal boiling characteristics (break-off diameters of the bubbles, frequency of break-off from the heater, growth rates, etc.) are almost completely lacking. The known studies contain incomplete information about the internal characteristics of boiling of nitrogen and oxygen at atmospheric pressure [5-8]. The data on the internal boiling characteristics are sometimes used in the derivation of formulas for the heat-transfer coefficients in the presence of bubble boiling [9-11]. The determination of the relationship between the internal characteristics and the intensity of heat transfer during bubble boiling would lead to the derivation of physically sound dependences of the heat-transfer coefficients not only on the pressure and heat flux density but also on the acceleration due to gravity.

The known experimental dependences pertaining to the dynamics of vapor bubbles, obtained from the study of boiling of water and organic liquids, cannot be directly extended to the case of boiling of cryogenic liquids if only due to certain characteristic features of the latter (for example, very small edge angles, relatively small amount of dissolved gases, and different law of their solubility compared to high-boiling liquids).

The object of the present work is an experimental investigation of the internal characteristics of nitrogen and oxygen boiling in a quite wide range of saturation pressures.

The experiments were conducted on the equipment described in [2]. A horizontal tube of 1Kh18N9T stainless steel with 8 mm diameter, 0.3 mm thickness, and 100 mm length was used as the heater. The outer surface of the tube was carefully processed; its purity after the final operation (polishing) was of the 10th class. The heating was done by a constant current. The heat flux density was calculated from the measured values of the current, the voltage, and the surface area of the heater.

The temperature of the heated surface was measured with three copper–Constantan thermocouples. The thermocouple junctions placed within the tube touched its upper generatrix; the reliability of the contact was ensured by a tight fitting of directing sleeves. The temperature of the inner surface of the tube was determined by averaging the thermocouple readings. The cold junctions of the thermocouples were placed inside the investigated liquid, which made it possible to measure the temperature head directly. In determining the temperature head correction was introduced for the temperature drop in the thermal resistance of the wall [2]. The temperature of the liquid was regulated with six copper–Constantan thermocouples placed in the operating volume. The emf of the thermocouples was measured with an R-306 potentiometer. The saturation vapor pressures of the liquid was measured by a vacuum manometer of type MO of 0.4 accuracy class.

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TABLE 1. Conditions of Experiments, Characteristic Times, and Growth Moduli

Liquid	p, bar	q, kW/m^2	ΔT, deg	$\bar{\beta}$, cm/sec^n	$\bar{n}$	τ_d, msec	τ_w, msec	τ_b, msec
Oxygen	0,1	17,7	6,0	3,5	0,53	21,7	28,0	49,7
	0,25	3,0	3,5	5,3	0,72	6,6	0,8	7,4
	0,42	3,0	3,2	0,83	0,47	2,4	1,2	3,6
	0,70	4,2	3,7	0,68	0,48	3,4	0,7	4,1
	1	3,0	3,8	0,40	0,46	5,0	1,0	6,0
	2	2,8	1,8	0,19	0,45	10,2	0,8	11,0
	4	2,8	1,4	0,10	0,43	24,0	2,9	26,9
	6	3,2	1,2	0,07	0,39	26,8	4,7	31,5
	8	2,8	0,9	0,03	0,25	31,2	5,6	36,5
Nitrogen	0,22	1,6	1,9	2,50	0,66	5,8	0,7	6,5
	0,45	1,3	1,6	0,90	0,55	3,4	0,8	4,2
	0,70	2,3	2,4	0,46	0,49	3,1	1,1	4,2
	1	2,2	2,2	0,45	0,51	3,5	0,3	3,8
	2	1,3	1,7	—	—	13,2	2,2	15,4

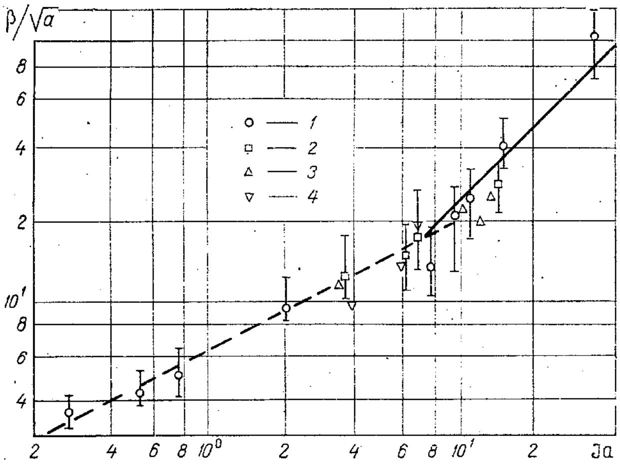

Fig. 1. Growth modulus as a function of Jacob number: 1) oxygen; 2) nitrogen; 3) nitrogen [6], 4) nitrogen [13].

The photographs were taken by a cinematographic camera SKS-IM in the transmitted light with a "Jupiter-6" tele-objective. A reversible 16-mm cinematographic film of type OCh-180 was used for the photographs. The rate of photographing was 3500 frames/sec. A Constantan wire of 0.17 mm diameter placed at a distance of 7-8 mm from the heated surface was used as the dimension scale and served as the reference for focussing the objective. Bubbles growing in isolation at the upper edge of the heater were chosen for photographs. The frames were processed using a 5PO-1 projection equipment with ×15 magnification. The vertical and horizontal dimensions of the bubbles were measured during the analysis of the frames. The time origin was referred to the frame preceding the instant of visible appearance of the bubble.

The motion picture of nitrogen and oxygen boiling was taken in the pressure range 0.22-2 and 0.1-8 bars, respectively. The regime parameters of each experiment are given in Table 1. The choice of the heat flux was governed by the necessity of obtaining isolated bubbles at the edge of the heater. At each pressure 25-30 bubbles were analyzed.

Growth of the Bubbles. On the frames corresponding to the instant of generation the bubbles had a hemispherical shape; at pressures of 0.25 bar and lower they had the shape of a segment. As the growth progressed, the bubbles acquired a shape close to spherical, slightly elongated along the vertical. At the instant of break-off at a pressure higher than 0.1 bar the shape of the bubbles was almost spherical (the difference between the vertical and horizontal dimensions of the bubble was of the order of 10%). At 0.1 bar pressure the bubbles had an irregular form at the instant of break-off. In this case the equivalent diameter of the bubble was calculated as the diameter of the sphere having the same volume as the bubble.

In the time interval $0.2\,\tau_d \le \tau \le \tau_d$ the growth of nitrogen and oxygen bubbles is satisfactorily approximated by the relation

$$R = \beta \tau^n. \quad (1)$$

For $\tau < 0.2\,\tau_d$ a considerable scatter of the experimental points up to ±30% occurs; this can be due to the error in the measurement of the bubble radius on the initial segment of its growth.

The experimental data on the growth of bubbles for $\tau > 0.2\,\tau_d$ were analyzed by the method of least squares for obtaining (1). The mean values of $\bar{n}$ and $\bar{\beta}$ are shown in Table 1 for the mean errors in their determination equal to ±20% and ±35%, respectively. As evident from the table, $\bar{n}$ and $\bar{\beta}$ have a tendency to decrease with the increase of the pressure.

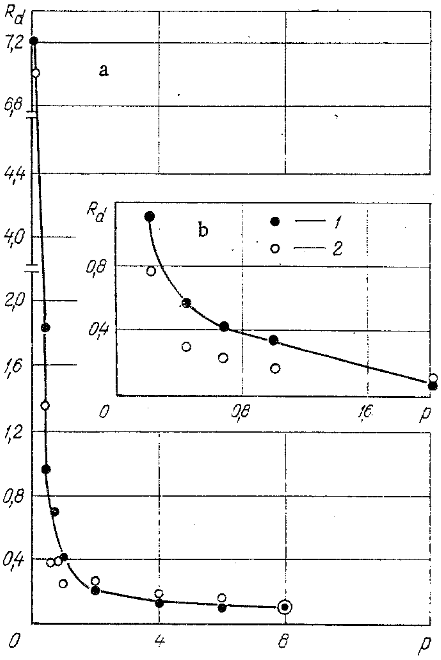

Fig. 2. Dependence of the break-off radius on saturation pressure (a, oxygen; b, nitrogen): 1) theory; 2) experiment; R_d in mm, p in bars.

Different values of n denote also different dimensionalities of growth moduli β. Therefore in order to be able to compare β for different values of p and with the theoretical formulas the curves of bubble growth were normalized to the dependence

$$R = \beta\tau^{1/2}. \qquad (2)$$

In the investigation of oxygen the normalized and true values of the growth moduli for certain pressures (p = 0.25, 6, 8 bars) are appreciably different; however, in the time interval from the generation to break-off the maximum difference between the true and the normalized curves does not exceed ±25 ; in all the remaining cases the two curves practically coincide.

The existing theories of growth of vapor bubbles [10, 12] lead to formula (2), where

$$\beta = C_\beta \mathrm{Ja}^{n_\beta} a^{1/2}. \qquad (3)$$

The values of the normalized quantity $\beta/\sqrt{a}$ are shown in Fig. 1 for all the investigated liquids. The dependence $\beta/\sqrt{a} = f(\mathrm{Ja})$ for oxygen clearly breaks up into two branches. At small Jacob numbers (0.3 ≤10; dashed line in Fig. 1) Labuntsov ($n_\beta = 0.5$; $C_\beta = 6$); type dependence holds; at larger Jacob numbers (7 ≤ Ja ≤ 35; continuous line in Fig. 1) Plesset – Zweek type dependence holds (n_β = 1, C_β = (2.5). The experimental results of [6, 13] agree satisfactorily with our results. In the entire pressure range the values of the mean growth moduli for oxygen and nitrogen are higher than the theoretical values [10, 12].

Break-off Characteristics of the Bubbles. Until recently the dimension of a vapor bubble during its break-off from the heater was estimated using the Fritz formula [9] obtained from an approximate solution of the problem of static stability of the bubble at a plane wall. A comparison of the experimental dependences of R_d on p and g with the Fritz formula shows that this formula is inapplicable for estimating the dimensions of vapor bubbles during boiling in a wide range of variation of pressure p and acceleration due to gravity g. The Fritz formula gives too weak a dependence of R_d on p [14-17] and too strong a dependence of R_d on g compared to the experiment; according to the experimental data the dependence of R_d on g is close to $R_d \sim g^{-1/3}$ [7].

The dependence of R_d on p and g, which is in satisfactory accord with the experimental data for sufficiently low pressures, is given by the formulas obtained from a comparison of the dynamic and buoyancy forces acting on the bubble breaking off from the heater. For a bubble growing in accordance with (2) all such formulas can be expressed in the form [18, 19]

$$R_d = C\beta^{4/3} g^{-1/3}, \qquad (4)$$

where C is a constant coefficient of the same order of magnitude as unity. The joint effect of the dynamic and static forces on the break-off radius R_d and the growth time τ_d of the bubble (the time interval from generation to break-off) has been investigated in [20] by one of the present authors. The computational formulas thus obtained are of the form

$$R_d = C_R \beta^{4/3} g^{-1/3}; \quad \tau_d = C_R^2 \beta^{2/3} g^{-2/3}, \qquad (5)$$

where

$$C_R = \left[1 + \frac{4 + 1.4\gamma}{M}\right]^{1/2} \left(\frac{M}{4}\right)^{1/3};$$

$$M = \left(1 + \frac{30\nu}{\beta^2} + \frac{6R_c\sigma}{\rho\beta^4}\right)\frac{\rho}{\rho - \rho''}; \quad \gamma = \frac{18\nu}{\beta^2}. \qquad (6)$$

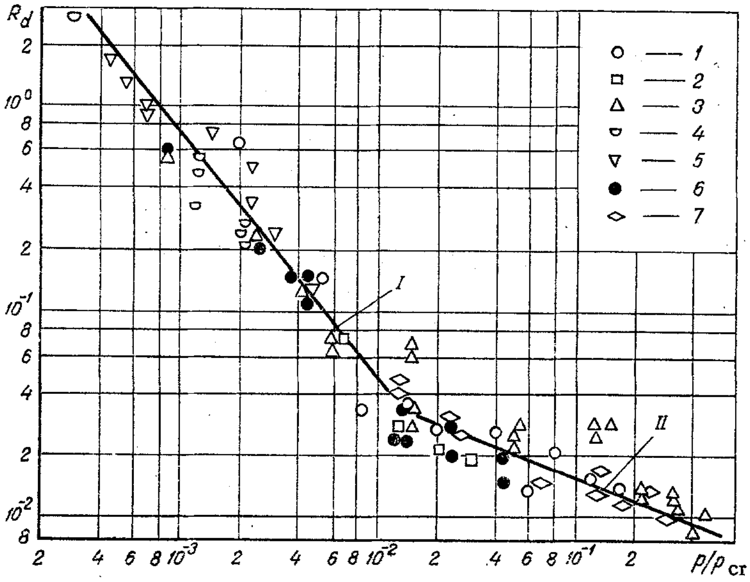

Fig. 3. Dependence of break-off radii of bubbles on the normalized pressure: 1) oxygen; 2) nitrogen; water: 3) from [14], 4) from [21], 5) from [16], 6) from [15], 7) Freon-12 [17]; R_d in cm.

The pressure dependence of the mean experimental values of the break-off radii of the bubbles is shown in Fig. 2. As seen from this figure, the radius R_d of the bubble at the time of break-off decreases with the increase of the pressure; the strongest dependence of R_d on p is observed at normalized pressures $p/p_{cr} < 0.01$. Figure 2 shows the values of R_d computed from formulas (5), (6) for the experimental values of the temperature heads and growth moduli (the use of averaged moduli does not bring in any significant change in the computed dependence). It is evident that formulas (5), (6) give a satisfactory agreement with the experimental data in the entire investigated pressure range. The steeply rising segments of the curves (p < 0.7 bar for oxygen, p < 0.4 bar for nitrogen) corresponds to the computation by formulas (5), (6) for the case, when the breaking off of the bubble is determined mainly by the inertia force of the liquid, i.e., $30\nu/\beta^2 + 6R_c\sigma/\rho\beta^4 \ll 1$, and the break-off regime is dynamic. The flat parts of the curves on the right (p > 2 bars for oxygen, p > 0.8 bar for nitrogen) correspond to the computation by formulas (5), (6) for the case when the decisive forces are the forces of surface tension; in this case $6R_c\sigma/\rho\beta^4 \gg 1$ and a quasistatic regime of break-off of bubble occurs. In the computations with formulas (5), (6) the radius of the center of vapor formation is determined in terms of the critical radius of vapor nucleation $R_c = 4\sigma T_s/L\rho''\Delta T$ [20].

The break-off radii of bubbles, obtained by different authors [14-17, 21] during boiling of different liquids, are shown in Fig. 3 as a function of the normalized pressure. In spite of the significant difference in the physical properties of the investigated liquids and the conditions of the experiments (shape and material of the heating surface, value of the temperature head) the dependences of the break-off radii on the normalized pressure are very similar. Two characteristic regions of variation of the break-off radius with the pressure change can be distinguished:

a) a region of dynamic regime of break-off vapor bubbles ($p/p_{cr} < 10^{-2}$), where the dependence of the bubble radius on the normalized pressure is generalized by the formula (curve I)

$$R_d = 1.9 \cdot 10^{-4}\,(p/p_{cr})^{-1.2}; \qquad (7)$$

b) a region of quasistatic regime of break-off of vapor bubbles ($p/p_{cr} > 2 \cdot 10^{-2}$), where this dependence is generalized by the formula (curve II)

$$R_d = 6.6 \cdot 10^{-3}\,(p/p_{cr})^{-0.4}. \qquad (8)$$

In formulas (7), (8) the values of R_d are in cm.

The average values of the growth time of vapor bubbles τ_d and the time $\tau_b = \tau_d + \tau_w$, where τ_w is the waiting time, are given in Table 1. It is evident that the values of τ_d and τ_b increase rapidly both in the region of large and small pressures. The frequency of break-off of the vapor bubbles $f = \tau_b^{-1}$ consequently falls off sharply at the edges of the investigated pressure range.

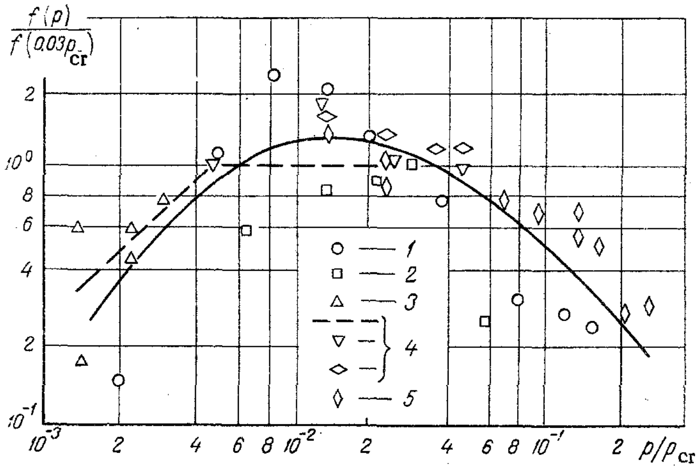

Fig. 4. Dependence of the dimensionless frequency of break-off of the bubbles on the normalized pressure: 1) oxygen; 2) nitrogen; water: 3) from [16]; 4) from [15]; 5) Freon-12 [17].

The dependence of the relative values of the break-off frequency $f(p)/f\ (0.03\ p_{cr})$ on the normalized pressure (p/p_{cr}) is shown in Fig. 4 for oxygen and nitrogen as well as water [11, 15] and Freon-12 [17]. Experimentally obtained values of the frequencies for $p = 0.03\ p_{cr}$ were taken as the reference values of f for water [15], Freon-12 [17], oxygen, and nitrogen: 75 sec^{-1} [15], 58 sec^{-1} [17], 125 sec^{-1} for oxygen, 260 sec^{-1} for nitrogen. In [16] the frequencies were not determined for this pressure. Considering that for the data presented in Fig. 4 for water as well as for the other liquids in the range $0.005\ p_{cr} < p < 0.05\ p_{cr}$ the break-off frequency of the bubbles may be assumed to be independent of the pressure within the limits of the error in their determination, the value $f = 33\ sec^{-1}$ at $p = 1$ bar was taken as the reference break-off frequency for [16]. In spite of the arbitrary nature of this dependence and large scatter of the experimental data obtained for different values of the temperature heads ΔT and heat flux densities q three characteristic regions of variation of f can be distinguished. In the region of low pressures $(p/p_{cr} < 5 \cdot 10^{-3})$ f decreases with p; in the region of high pressures $(p/p_{cr} > 5 \cdot 10^{-2})$ f decreases with increase in p; and in the intermediate region the variation of f for each liquid lies within the limits of error in the determination of f.

A qualitative explanation of the experimentally observed variation of R_d and f with pressure can be obtained from an analysis of formulas (5), (6), which has been done in [20] for dynamic and quasistatic regimes of break-off of vapor bubbles corresponding to low- and high-pressure regions. It follows from (5), (6) that in the dynamic regime the bubble radius decreases sharply with the increase in pressure. In the static regime also the pressure increase results in a decrease of the bubble radius but the pressure dependence is weaker. It is seen from Figs. 2 and 3 that there is not only a qualitative but also a satisfactory quantitative agreement between the experimental data and the theoretical estimates given in [20].

According to [20] the break-off frequency, determined as τ_d^{-1} in the dynamic regime, increases with the pressure, while it decreases in the quasistatic regime; this is in accord with the data presented in Fig. 4. The behavior of f has a very strong dependence on the temperature head and the waiting time τ_w, which is not taken into consideration in formulas (5), (6). One thing that can be stated with certainty is that f increases with p in the region of small pressures and decreases with the increase of p in the region of large pressures.

The data presented in Figs. 3 and 4 permit the conclusion that in the case of boiling in the regime of solitary bubbles the boundary between the dynamic and quasistatic regimes of break-off of vapor bubbles (between "low" and "high" pressures) lies in the range $0.005\ p_{cr} < p < 0.05\ p_{cr}$ with the mean value $p \approx 0.02\ p_{cr}$.

NOTATION

D	is the diameter;
R	is the radius;
τ	is the time;
τ_w	is the waiting time;

C_β, C, C_R	are the numerical coefficients in the formulas for β and R_d, respectively;
g	is the acceleration due to gravity;
a	is the thermal diffusivity;
n, n_β	are the power exponents;
p	is the pressure;
ΔT	is the temperature head;
β	is the growth module of bubble;
ν	is the kinematic viscosity;
ρ, ρ''	are the densities of liquid and vapor, respectively;
σ	is the surface tension;
f	is the break-off frequency of bubbles;
R_c	is the radius of center of vapor formation;
q	is the heat flux density;
$Ja = \lambda \Delta T / L\rho'' a$	is the Jacob number.

Subscripts and Superscripts

d	denotes the break-off conditions;
cr	denotes the critical point.

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