DETACHMENT FREQUENCY AS A FUNCTION OF SIZE FOR VAPOR BUBBLES

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It is assumed that the bubble detachment frequency for the heater surface is determined by the oscillation frequency of the particles in the surrounding liquid. A relation is drawn up between the frequency and the detachment diameter for bubbles.

The major parameter characterizing heat transfer in boiling is the product fD_0; it has been shown [1] that vapor bubbles are detached from a heater surface at equal intervals and have identical size for a given nucleation center. It has also been found that fD_0 is constant, i.e.,

$$fD_0 = \text{const.} \tag{1}$$

It has [2] been stated that this product may be expressed in terms of the physical properties of the liquid by a relationship of the form

$$fD_0 = 0.59\left[\frac{g^2\sigma(\gamma' - \gamma'')}{\gamma'^2}\right]^{0.25}. \tag{2}$$

It has been observed [3, 4] that (2) does not apply for high heat fluxes, the actual detachment frequency being considerably higher than that by (2).

It has been suggested [4] that the detachment frequency be calculated from the following formula for conditions close to the critical one:

$$fD_0^{0.5} = \left[\frac{4g(\gamma' - \gamma'')}{3\xi\gamma'}\right]^{0.5}. \tag{3}$$

Figure 1 shows the dependence of f on D_0 as calculated from (3), which is shown by dot-and-dash line; in fact the calculated line agrees very well with experiment.

Equation (3) differs from (2) in that D_0 enters to the power $n = 0.5$; the same value of n with D_0 has been obtained [5] in studying the detachment of bubbles in relation to diameter for boiling liquid nitrogen.

These examples show that n takes values dependent on the heat flux. It has been observed [6] that n has to vary from $-1/2$ to -2 in order to fit the results from various sources, from which it has been concluded that there is no single relation of f to D_0 applicable to the entire range of bubble boiling. On this basis, three regions were distinguished [6]: 1) the hydrodynamic region, where $n = -1/2$; 2) the transition region, where $n = -3/4$; 3) the thermodynamic region, where $n = -2$.

It was assumed [6] that $n = -1$ should not be considered in exact theoretical analyses, because the result $f \sim D_0$ is approximate and applies only for very small bubble sizes. It is clear that further studies are needed to establish the full details of this process.

We have related the detachment frequency to the diameter via the speed of motion of the bubbles; an analogous approach is found in [1], but the difference from the latter is that the detachment frequency and diameter were considered as certain characteristics of a wave process arising in the liquid at the start of bubble growth, so the relation between f and D_0 is inherent in this case.

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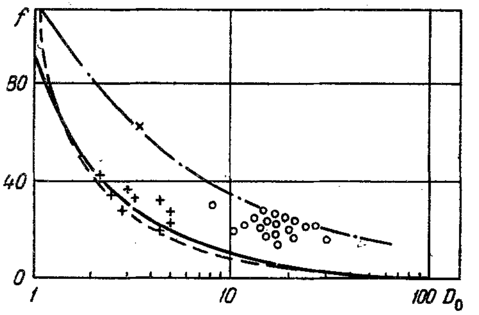

Fig. 1

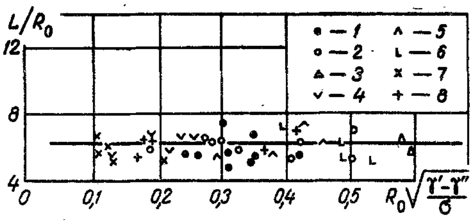

Fig. 2

Fig. 1. Detachment frequency f, $\sec^{-1}$, as a function of diameter D_0 (mm) of bubbles. Experiments of [4].

Fig. 2. Experimental data of [10] confirming the proportionality factor in (5): 1-3) water with $0.8 \cdot 10^4$, $6.47 \cdot 10^4$, and $2.65 \cdot 10^4$, N/m^2, 4-6) benzene with $9.8 \cdot 10^4$, $3.68 \cdot 10^4$, and $1.96 \cdot 10^4$ N/m^2, 7 and 8 ethanol with $9.8 \cdot 10^4$ and $4.31 \cdot 10^4$ N/m^2.

The regular bubble production results in the periodic displacement of the surrounding liquid, which is essentially oscillatory; the opposing flows of liquids at the root of the bubble create at the mouth of a depression an additional alternating pressure; a new bubble can grow only when the pressure at the mouth becomes equal to the total pressure at the surface of the heater. The periodicity in the repetition is due to the inertia of the liquid, which considerably exceeds the inertia in the vapor. Then the bubbles on appearing produce a perturbation in the liquid that is repeated with a frequency f, and this perturbation propagates into the liquid with some velocity v, which is determined by the size of the bubbles and the properties of the liquid. The repetition frequency of any wave process is related to the propagation velocity by

$$f = v/L. \tag{4}$$

It has been established [7] that bubbles moving in a liquid excite waves of length

$$L = 2\pi R_0. \tag{5}$$

It follows from (5) that the distance between two bubbles in each sequence should be proportional to the size; the coefficient of proportionality $c = L/R_0 = 2\pi$ retains the same value no matter what the conditions for the boiling.

To test this conclusion we measured the distances between bubbles on cine films recorded by N. N. Mamontova in examining the detachment frequency and diameter for boiling in various liquids. Figure 2 shows these results, which indicate that the mean value of the constant actually can be taken as 2π.

Then the detachment frequency is related to bubble size and velocity by

$$f = v/2\pi R_0. \tag{6}$$

It has been found by experiment [3, 4] that the speed of translational motion of bubbles directly before detachment equals the speed of free rise; consequently, at the end of growth the acceleration in the translational motion becomes zero, while the speed becomes constant and equal to the rise speed. It is found [7] that the free motion of a rising single gas bubble is given by

$$v = \left[\frac{gR_0(\gamma' - \gamma'')}{\gamma' + \gamma''} + \frac{g\sigma}{R_0(\gamma' + \gamma'')}\right]^{1/2}. \tag{7}$$

Experiment [6] shows that the speed of vapor bubbles agrees with that of gas bubbles when the heat flux is low, i.e., when the vapor bubbles are produced singly, so it is correct to assume that (7) applies also for single vapor bubbles.

We substitute (7) into (6) to get

$$f = \frac{1}{2\pi R_0}\left[\frac{gR_0(\gamma' - \gamma'')}{\gamma' + \gamma''} + \frac{g\sigma}{R_0(\gamma' + \gamma'')}\right]^{1/2}. \tag{8}$$

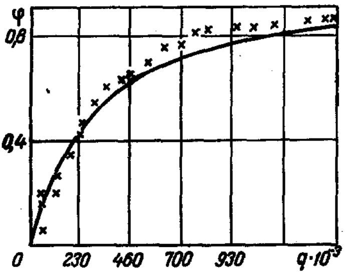

Fig. 3

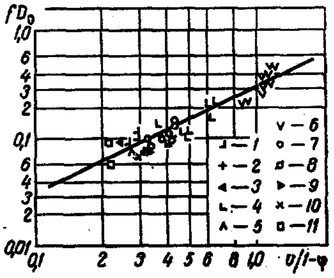

Fig. 4

Fig. 3. Comparison of experimental data and predicted φ; q in 10^{-2} W/m^2.

Fig. 4. Relationship $fD_0 = F(v/1-\varphi)$, m/sec (atmospheric pressure): 1) water [1]; 2) water [3]; 3) water [10]; 4) water [11]; 5) water [14]; 6) methanol [4]; 7) methanol [9]; 8) methanol [12]; 9) ethanol [10]; 10) CCl_4 [3]; 11) n-pentane [13].

The broken line in Fig. 1 compares the results calculated from (8) and recorded by experiment [1]; the solid line in this figure represents calculations by relationship proposed by Jakob. Formula (7) is correct for the motion of a single bubble, so (8) and Jakob's formula characterize the stage in boiling where there is no interaction between adjacent chains of bubbles, i.e., at low peak loading.

If (8) is used for practical calculations, one should use in (6) the rise velocity v corresponding to the dimension of the detached bubbles; four regions may be distinguished [8] as regards the form of $v = F(D_0)$. Equation (7) applies for the third and fourth regions.

To elucidate the increased detachment frequency at high heat loads we need to remember the structural changes that occur in the boundary two-phase layer when the heat loading is high.

Increase in heat loading is accompanied by increase in the concentration of nucleation centers at the surface; the vapor content φ of the boundary layer then also increases, while the quantity of liquid at the boundary decreases. The higher the heat flux, the higher the vapor content in the boundary layer, and the less the liquid remaining there, and reduction in the liquid in that layer means that the films of liquid between adjacent bubbles become thinner. In that case, the bubbles begin to interact, and the more so the higher the vapor content. The bubbles growing at adjacent centers interact via the intervening thin film of liquid, and begin to assist one another, so the velocity increases to v_φ. In other words, the restriction on the the slope for free increase in horizontal size is compensated by increased speed in the vertical direction, which is the reason for the change in detachment frequency and diameter.

Then the bubble speed, which equals v for $\varphi \approx 0$, rises as the bubbles begin to interact and becomes equal to v_φ at some steam content φ; the above view of the mechanism indicates that the speed of the bubbles for a vapor content φ may be expressed via the speed of the individual bubbles as in

$$v_\varphi = \frac{v}{1-\varphi}. \tag{9}$$

We replace v by v_φ in (8) to get that the bubble detachment frequency at high heat loadings is

$$f = \frac{1}{2\pi R_0 (1-\varphi)} \left[\frac{gR_0(\gamma' - \gamma'')}{\gamma' + \gamma''} + \frac{g\sigma}{R_0(\gamma' + \gamma'')} \right]^{1/2}. \tag{10}$$

Calculations from (10) coincide with the line defined by (3): for $\varphi = 0.780$ for water, or 0.750 for methanol.

Equation (10) is common to all regions of bubble boiling; as $\varphi = 0$ for single bubbles, (10) in that case becomes (8) as a partial case.

From (10) we conclude that: 1) if the detaching bubbles are sufficiently large, the first term inside the square brackets is much larger than the second, and then $f \sim 1/D_0^{0.5}$, i.e., $n = -1/2$; 2) if the two terms within the square brackets are equal (this occurs for $R_0 = [\sigma/(\gamma' - \gamma'')]^{0.5}$), then f is proportional to $1/D_0$, i.e., $n = -1$; 3) if the vapor bubbles are small, we can neglect the first term in the square brackets, and then $f \sim 1/D_0^{3/2}$, i.e. $n = -3/2$.

Then (10) contains all the cases observed in the various experiments reported in the literature.

A full test of (10) requires knowledge of the vapor content as a function of heat flux; but at the present time there is no suggestion in the literature on how that content φ for a boundary layer in a two-phase mixture varies for a variety of pressures, so we have tested (10) for pressures not very greatly different from atmospheric. Under these conditions, φ in the boundary layer may be defined as the ratio of the reduced evaporation rate

$$w'' = q/r\gamma'' \tag{11}$$

to the true speed of a bubble within this layer. The vapor phase is transported by motion of the bubbles, so one expects that the true speed of the vapor will not differ greatly from the quantity defined by (9), especially at elevated φ; then

$$\varphi = \frac{w''(1-\varphi)}{v}, \tag{12}$$

where v as before is defined by (7)

From (11) and (12) we have

$$\varphi = \frac{q}{q + r\gamma'' v}. \tag{13}$$

Figure 3 compares (13) with experiment; the curve from (13) satisfactorily fits the data.

Subsequently, to test (10) we took φ as having the value of (13); Fig. 4 shows results from various sources processed in accordance with (10).

Note that we have used experimental results only from papers in which values were given for the heat fluxes at which f and D_0 were measured.

It is clear from Figure 4 that the points fit closely around the straight line defined by

$$fD_0 = \frac{1}{\pi} \cdot \frac{v}{1-\varphi}. \tag{14}$$

We conclude that it is incorrect to say [6] that a single equation cannot describe the dependence of f on D_0; various values of n occur in the relation $f \sim D_0^n$ because the actual speed of the bubbles changes with the heat flux in accordance with a rather complicated variation in φ. The problem is to determine reliably φ and the bubble rise speed v; if these quantities are known, then the dependence of f on D_0 is easily derived from (10).

NOTATION

f	is the frequency of bubble datachment;
R_0, D_0	are the radius and diameter of bubbles;
γ', γ''	are the densities of liquid and vapor;
σ	is the surface tension coefficient;
g	is the gravitational acceleration
v	is the bubble velocity;
φ	is the vapor content;
w''	is the rate of evaporation;
q	is the specific heat flux;
r	is the latent heat of evaporation.

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