THE SHAPES AND SIZES OF VAPOR BUBBLES DURING BOILING ON DOWNWARD-FACING FLAT SURFACES

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The effect of the properties of the liquid (water, ethanol, nitrogen, and oxygen) on the shapes and sizes of bubbles during boiling on downward-facing plates has been investigated.

It is known that the orientation of a flat heat-transfer surface can greatly influence the heat-transfer characteristics during nucleate boiling, especially at angles ϕ exceeding 90° [1-3]. In the latter case the solid surface makes the evacuation of the vapor being formed into the bulk of the liquid more difficult; this effect is greatest for planes facing downwards ($\phi = 180°$). On such surfaces the value of q_{cr} may be several times smaller than in the case when $\phi = 0°$ [1, 4, 5]. On the other hand, the heat-transfer coefficients are larger than on the same surfaces turned upwards [5-7]. It should be noted that the theory of boiling heat transfer on downwards-facing surfaces has still not been fully developed. Only partial empirical relationships exist for determining the heat-transfer characteristics; these have been obtained by the generalization of very scanty experimental data [1, 5].

It is clear that the special features of heat transfer during boiling on downward-facing planes are related to the features of the growth and evacuation of the vapor bubbles. However, the dynamics of bubbles underneath heat-transfer surfaces remains a little-studied subject. Only qualitative information exists. Thus, it was noted by the authors of [6] (who were among the first to describe the behavior of bubbles underneath heat-transfer surfaces) that "the growing bubble initially has a spherical shape, which in the course of growth and coalescence with neighboring bubbles is transformed to the shape of a flat spheroid slowly sliding along the surface." On the basis of visual observations, the authors of [6] proposed that the intensification of heat transfer in the present case is a consequence of the increase of the area of the liquid microlayer under the growing bubble during the flattening of the latter under the influence of buoyancy forces, and also of the increase in the time of contact of the bubbles with the heat-transfer surface. These observations are in agreement with the conclusions of other studies where the "microlayer" hypothesis is supported also [2, 3, 5, 7]. None of the studies, however, has provided quantitative measurements of the bubble sizes. No attempt has been made to theoretically describe the shapes and sizes of the vapor bubbles.

In the present paper we propose to use a quasi-steady-state model of the growth of a vapor bubble according to which the shape and size of the latter at each moment of time corresponds to the shape and size of an equilibrium gas bubble of the same volume. This model gives good results for bubbles on surfaces facing upwards in the case when the Jakob number is not very large.

The problem of the equilibrium shape of a gas bubble underneath a flat solid surface submerged in a liquid was solved in [8] as a special case of the problem of axisymmetric liquid surfaces. By means of the numerical integration of the equilibrium differential equations, a family of parametric curves was obtained which gives the shapes of the bubble surfaces in dimensionless form for various values of the wetting angle; the linear dimensions are expressed as fractions of the capillary constant. Figure 1 shows examples of the change in the bubble shapes as the volume increases in terms of the dimensionless coordinates $\tilde{H}_{max} = H_{max}/b$, $\tilde{D}_{max} = D_{max}/b$ for two values of α. It can be seen that bubbles of small volume have shapes close to spherical ($\tilde{H}_{max} \approx \tilde{D}_{max}$); starting at some volume, the growth of $\tilde{H}_{max}$ ceases as $\tilde{D}_{max}$ increases, and the bubble grows only in the radial direction, retaining a constant height of about 2b.

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TABLE 1. Conditions of Carrying Out the Experiments and Results of Evaluating the Experimental Data

Liquid	Water				Ethanol	Nitrogen		Oxygen
Pressure, 10^5 Pa	1,0				1,0	0,2—9,0	1,0	1,0
Temperature, °K	293		373		293	66,0—102,3	77,3	90,2
b, mm	2,73		2,50		1,69	0,765—1,17	1,06	1,08
Solid surface	Stainless steel, aluminum alloy				Aluminum alloy b	Aluminum alloy, copper	Stainless steel	Copper
	unheated			heated	unheated	heated	unheated	heated
ΔT, K	0*	0	0	2,5—20,0	0	0,23—5,22	0	2,0—4,0
Ja	0	0	0	3,6—29,0	0	0,4—1,9	0	4,3—8,6
No. of bubbles	15	34	26	66	22	94	18	34
$\bar{S}_{min}$, %	6,9	22,9	34,5	16,2	22,1	26,8	12,5	19,5
α_0, deg	90	50	40	20	30	10	10	30
$\bar{S}(\alpha = 0°)$, %						31,9	18,0	42,5

* Surface coated with grease.

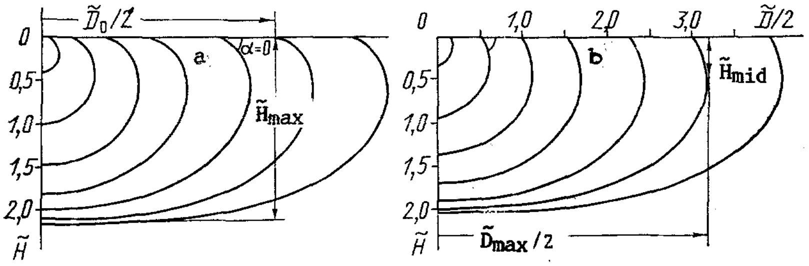

Fig. 1. Evolution of the shapes of equilibrium gas bubbles underneath a flat solid surface according to [8]: a) α = 0°; b) α = 50°.

The objective of the present study was to obtain data on the sizes of vapor bubbles during boiling on downward-facing flat surfaces and to compare these data with the values calculated from the theory of [8]. It should be noted that clearly this comparison is carried out for the case of the equilibrium gas bubbles for which the theoretical solution was derived. In a preliminary series of experiments, measurements were therefore made of the dimensions of equilibrium air bubbles of various volumes in distilled water and in 96% ethanol solution. In the main series of experiments, measurements were made of the dimensions of vapor bubbles during the boiling of water and oxygen at atmospheric pressure and also during the boiling of nitrogen over a wide range of pressures, which made it possible to vary the value of b for the same liquid. In order to compare the experimental data with the calculated values over as wide as possible a range of the parameters, liquids were chosen for the experiments which had quite different values of the capillary constant and wetting angle. Thus, while for nitrogen, oxygen, and ethanol α = 0-10.5° [9, 10], for water α = 0-108° [9]. With the objective of expanding the range of α towards larger values, one of the experiments with the air bubbles in water was carried out on a surface covered with grease

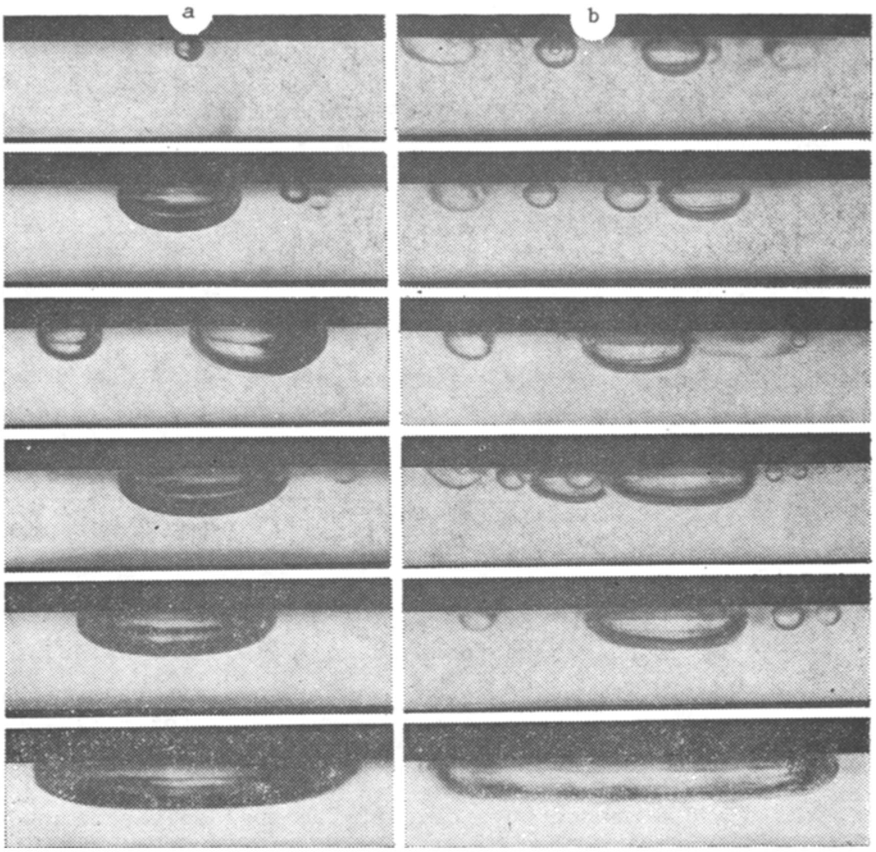

Fig. 2. Changes in the shapes and dimensions of bubbles in the experiments: a) equilibrium air bubbles in water at room temperature; b) boiling of nitrogen at atmospheric pressure.

(vaseline). The conditions under which the experiments were carried out are given in Table 1.

The dimensions of the growing vapor bubbles and the stationary gas bubbles were determined by using photographs in a transmitted light "Zenit-E" apparatus with an "Industar-50-2" lens and an extension ring. The exposure time was 0.002 sec. The experiments with water and ethanol were carried out in a glass vessel with flat walls, while the experiments with nitrogen and oxygen were carried out in a metallic cryostat with windows. A steel strip used as a linear scale was placed below the flat surface of copper, stainless steel, or aluminum alloy. A plate which was circular in plan and of 50-mm diameter, fitted with an electric heater, was used in the experiments with boiling; in the experiments with gas bubbles the diameters were up to 100 mm. The distance from the scale strip to the plane of the plate varied from 4 to 10 mm; the error in fixing the angle of the plate at $\phi = 180°$ was ±1°. After developing the photographic film prints were made at an enlargement of 2.5-7.5 times. Figure 2 shows typical shapes of the vapor and gas bubbles, which illustrate the similar nature of the change of the height H_{max} with increase of the maximum diameter D_{max}. The latter value reached 40 mm and greater; in the experiments with the cryogenic liquids vapor formations of such large size could result so as to completely cover the heat-transfer surface, which therefore corresponded to film boiling and not nucleate boiling. Photographs with film boiling were obtained for extending the range of sizes: a vapor film with a smooth surface can be regarded as one large bubble.

The calculated shape of the bubble profile for the given bubble volume is given in the theory of [8] by a curve which does not have an analytical expression. For comparison with the theory, the bubble contour was therefore characterized by four dimensions: the maximum height H_{max}, the maximum diameter D_{max} and the corresponding height H_{mid}, and the diameter of the base D_0 (see Fig. 1). The values of these quantities were determined from the photographic prints; the number of bubbles evaluated at each combination of conditions is indicated in Table 1. The value of D_{max}, which is the most sharply defined and has the largest absolute value of the four variables, was chosen as the basis for the comparison with the

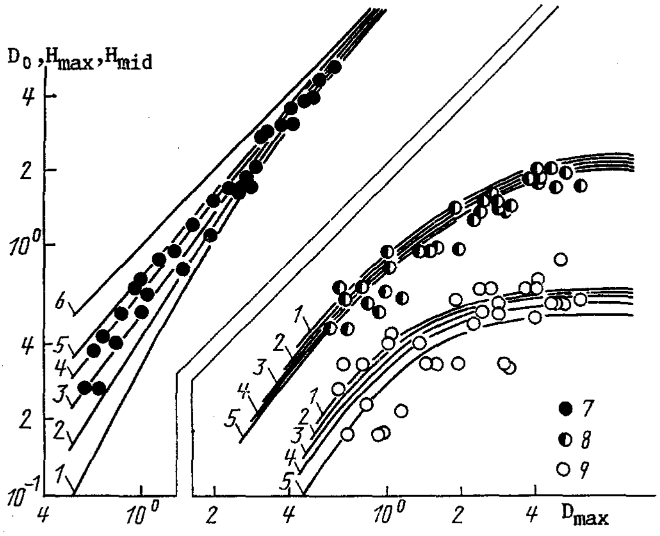

Fig. 3

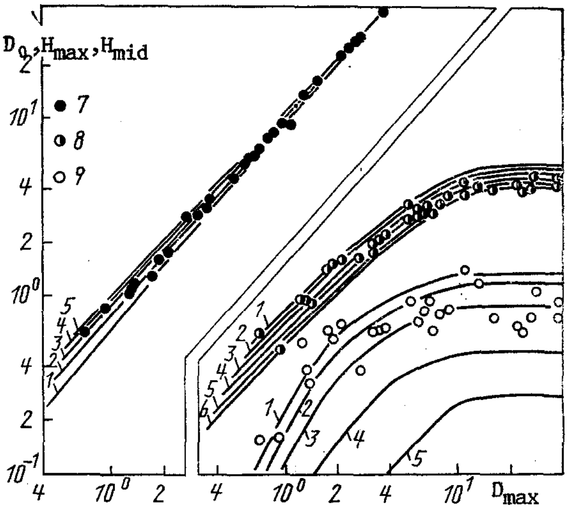

Fig. 4

Fig. 3. Comparison of the experimental data on bubble sizes during the boiling of oxygen with values calculated according to [8]: lines 1-6 correspond to α = 0, 10, 20, 30, 40, and 90°, respectively; the points 7-9 correspond to: 7) D_0, mm; 8) H_{max}, mm; 9) H_{mid}, mm.

Fig. 4. Comparison of the experimental data on the sizes of equilibrium gas bubbles in water at room temperature with values calculated according to [8]: lines 1-6 correspond to α = 40, 50, 60, 70, 80, and 90°, respectively; the points 7-9 are the same as in Fig. 3.

calculations. Figures 3 and 4 present typical data on the dependence of H_{max}, H_{mid} and D_0 on the values of D_{max} for vapor and gas bubbles. It is clear that the smaller the absolute value of the size, the greater is the scatter of the experimental data. This is explained by the increase in the relative error in determining the dimensions. An evaluation of the error indicates that it does not exceed 40% when $H > 0.43$ mm for water, $H > 0.37$ mm for nitrogen, $H > 0.35$ mm for oxygen, and $H > 1.08$ mm for ethanol. Data on sizes smaller than these values cannot be regarded as sufficiently reliable.

Similar relationships to those shown in Figs. 3 and 4 for $H_{max}(D_{max})$, $D_0(D_{max})$, and $H_{mid}(D_{max})$ were also obtained in all the other experiments. For quantitatively comparing the data which were obtained with the calculations according to [8], the corresponding curves were constructed for a series of values of the wetting angle α from 0 to 90° in steps of 10°. The mean square deviations of the experimental data on H_{max}, H_{mid}, and D_0 from the calculated values were computed for each of the 10 values of α. The relationship $\bar{S}(\alpha)$ had the form of a curve with a minimum; the value of α corresponding to the minimum deviation was taken as the optimum value α_0. The optimum value of the angular parameter could appear to be different for each of the values H_{max}, H_{mid}, D_0. For the combined evaluation of the agreement of the experimental values with the calculated data an overall relative mean square deviation was therefore computed with respect to all three dimensions. The results of the calculations of $\bar{S}$ are shown in Table 1. It can be seen that there are no significant differences in the values of $\bar{S}$ between the vapor and gas bubbles; it should be noted that in all cases the value of H_{mid} provides the main contribution towards $\bar{S}$. Thus, the theory of [8] can be applied for evaluating the shapes and sizes of gas bubbles which are growing and moving with respect to the boiling surface, and the error will be no larger than for equilibrium gas bubbles. The small influence of the dynamic effects is obviously explained by the fact that the zone of nucleate boiling on downwards-facing planes is restricted to low values of q_{cr} and of the temperature driving force; the small degree of overheating also leads to relatively low values of the Jacob number (see Table). This range of Ja corresponds to the quasi-steady-state and transitional regimes of the growth of the vapor bubbles, where the inertia forces of the liquid reaction are small [11].

It must be noted that the values of α_0 which have been found to give the best agreement between the experimental values and the calculations appear to be overestimated compared to the wetting angles given in the literature for ethanol and the cryogenic liquids. However, even calculations for the case $\alpha = 0°$ give values of $\bar{S}$ which are not too large, since the curve $\bar{S}(\alpha)$ has quite a flat minimum. For water the values of α_0 fall within the range of recommended wetting angles, with the maximum value of α_0 corresponding to the surface covered with grease. In general, direct comparison of the values of α_0 and α is possible only to a first approximation, since during boiling, for instance, it is not possible to distinguish in the photographs the bubbles which are separating (the thickess of the liquid layer beneath them amounts to 1-2 μm [12]), for which the concept of a "wetting angle" loses its significance, from the bubbles which are still in contact with the solid surface and which have a well defined value of α. In fact, a nominal value of the wetting angle is used successfully in the calculations which may differ from the (real) wetting angle for a whole series of reasons: because of the motion of the bubble, interactions with its neighbors, the roughness of the solid surface, etc.

The photographs of boiling give the instantaneous dimensions of a number of bubbles which are at different stages of growth. By arranging the bubbles in the order of increasing dimensions, it is possible to regard that to a first approximation as a representation of successive images of the same growing bubbles. Thus, it can be concluded that the growth of the bubbles on downward-facing planes has three stages, including an initial stage in which the bubble has a shape close to spherical and grows in all directions, and a final stage where the bubble has a constant height, and only its diameter increases.

NOTATION

$b = \sqrt{\sigma/g(\rho - \rho_v)}$, capillary constant, m; c_p, specific heat capacity of the liquid at constant pressure, J/(kg·K); D, diameter, m; H, height, m; $Ja = c_p\rho\Delta T/L\rho_v$, Jacob number; L, heat of vaporization, J/kg; q_{cr}, first critical heat flux density, W/m^2; $\bar{S}$, mean square relative deviation, %; ΔT, temperature difference, °K; α, wetting angle, deg; α_0, optimum value of the angular parameter, deg; ρ, ρ_v, densities of the liquid and vapor, kg/m^3; σ, surface tension coefficient, N/m; ϕ, angle between the normal to the heat-transfer surface and the vertical, deg.

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