MICRO-MOTION-PICTURE STUDY OF THE MECHANISM OF BUBBLE GROWTH AND SEPARATION DURING BOILING OF LIQUIDS ON SMOOTH HORIZONTAL SURFACES AND AT PORES

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The mechanism of bubble separation from a horizontal surface with poor wetting properties has been investigated by means of high-speed motion-picture photography. Film showing the microscopic process of bubble growth and separation from cylindrical pores in a horizontal surface has been obtained for the first time.

It has been theoretically established that in nucleate boiling it is possible to observe two different types of separation of vapor bubbles from a smooth heating surface depending on the value of the contact angle.

In the case of small contact angles $\Theta < 90°$ the breakaway volume corresponds to the maximum bubble volume and is given by the Fritz formula

$$D_0 = \varphi(\Theta)\, a = \varphi(\Theta) \sqrt{\sigma/g(\rho' - \rho'')} . \quad (1)$$

The bubble separates completely from the solid surface, after which the surface remains free for a certain time until a new bubble is formed. The mechanism of this type of separation was investigated by Fritz [1, 2] and is in complete correspondence with the experimental data at contact angles $\Theta < 90°$.

In the case of a surface with poor wetting characteristics at large contact angles $\Theta > 90°$ Nesis [3, 5] theoretically predicted the possibility of another type of separation. According to his conclusions, the breakaway volume of the vapor bubble is less than its maximum volume and is given by Eq. (1). Separation occurs along the neck of the bubble, and a vapor embryo, from which the new bubble grows, is left on the surface. For angles $\Theta > 100°$ the breakaway volume does not depend on the contact angle and is given by the equation

$$D_0 = 2a = 2\sqrt{\sigma/g(\rho' - \rho'')}, \quad (2)$$

i.e., it is determined by the surface tension of the liquid and the densities of the liquid and its vapor. Theoretical calculations [5] also make it possible to calculate the maximum bubble height before separation and the height of the neck for different contact angles.

The kinetics of formation, growth, and separation of bubbles from pores, cracks, and surface scratches is also of considerable importance in connection with the theory of boiling.

The mechanism of bubble growth from cylindrical pores was first examined by Nesis [3]. From the condition of equilibrium of the liquid and the solid surface he obtained relations characterizing the activity of wettable and nonwettable pores. Moreover, he predicted that the base of the bubble must vary with the degree of wetting; thus at acute contact angles the base of the bubble almost always remains "attached" to the edge of the pore, whereas at large contact angles the base of the bubble leaves the edge of the pore, spreading out over the surface.

As far as we know, there have so far been no detailed experimental studies of the vapor bubble dynamics on smooth nonwettable surfaces and at pores for arbitrary contact angles. Accordingly, the aim of our research was to verify the theoretical conclusions of [3, 5] concerning the role of the contact angle in the

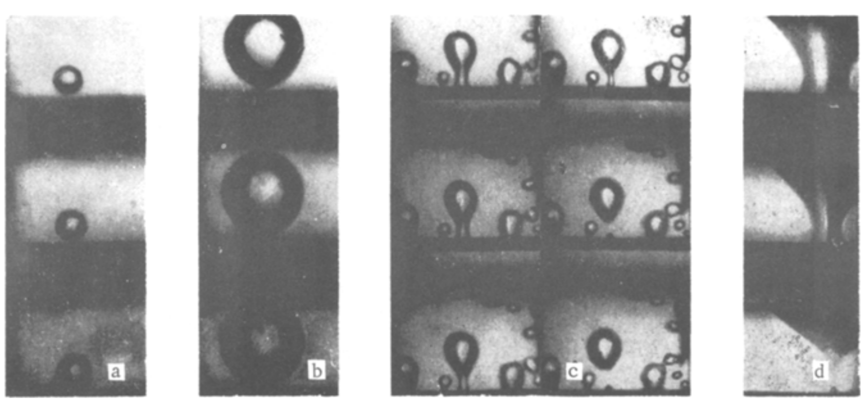

Fig. 1. Separation of bubble from smooth horizontal heating surface: a) from copper surface cleaned with a weak solution of sodium sulfate, $\Theta = 20°$; b) from a technically pure copper surface, $\Theta = 50°$; c) from a stainless steel surface coated with paraffin solution, $\Theta = 110°$; d) from a paraffin-coated nickel surface, $\Theta = 90°$.

mechanism of bubble separation from smooth surfaces and cylindrical pores.

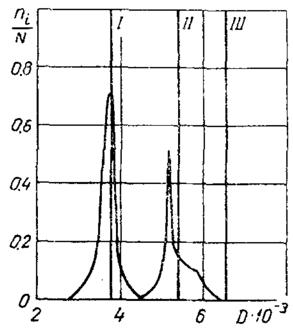

Fig. 2. Probability density functions for the bubble breakaway diameter D_0, m. The vertical lines correspond to theoretical values of the diameters calculated from Eqs. (1) and (2): I) from Fritz's formula for $\Theta < 90°$; II) from Nesis's formula for $\Theta > 100°$; III) from Fritz's formula for $\Theta > 100°$.

In order to obtain large contact angles the metal surfaces were coated with surface-active agents by the method described in [6–8]. In this way it proved possible to obtain contact angles in the range from 80° to 130°.

We studied the mechanism of bubble growth and separation during boiling of distilled water, degassed by prolonged boiling, at atmospheric pressure and saturation temperature. The temperature of the heating surface was measured with a copper-constantan thermocouple.

The process was filmed using an SKS-1M high-speed motion-picture camera at speeds of from 900 to 3000 frames per second. To make a detailed study of bubble growth and separation, in a number of cases we placed a microscope with an objective magnification of 11×, 20×, and 30× between the vessel and the camera. The cylindrical pores were of different depth and different diameter (from $2 \cdot 10^{-4}$ to $1 \cdot 10^{-3}$ m).

As indicated above, in each of the experiments the surface was treated so as to obtain bubbles with a given contact angle. However, the contact angles proved to be somewhat different for different centers of vaporization, which led to a variation in breakaway diameter and breakaway frequency. At average heat loads so many boiling sites appeared on the paraffined surface that the images of the bubbles overlapped and could not be investigated.

In order to obtain a smaller number of boiling sites heat fluxes of from $2.43 \cdot 10^4$ to $5.0 \cdot 10^4$ W/m^2, corresponding to a temperature head of from 0.5° to 1.8° C, were supplied to the heating surface. This made it possible to study the process of growth and separation of a single bubble at each site.

In filming through a microscope only one center of vaporization appeared in the field. In view of these specific experimental conditions the number of centers of vaporization per unit of surface and the bubble breakaway frequency were not computed.

Experimental results. At small contact angles the mechanism of bubble growth and separation is in good qualitative and quantitative agreement with the theory of Fritz [1, 2]. The bubble separates completely from the surface, and the breakaway diameter is given by Eq. (1).

The separation process is illustrated in Fig. 1. Photos a, b, and d were obtained by filming through a microscope with 11-fold magnification; c without a microscope.

In Fig. 2 curve I shows the distribution of bubble diameters for contact angles of 60°–70°. The straight line corresponds to the average breakaway diameter calculated from (1) for angles in this interval.

At contact angles exceeding 90° the mechanism of bubble growth and separation from the heating surface changes substantially. Separation takes place along a neck. Part of the vapor phase remains on the heating surface to form the nucleus of a new bubble (Fig. 1).

Measurements showed that the breakaway diameter is less than the maximum diameter and at angles $\Theta > 100°$ does not depend on the contact angle. As may be seen from the table and Fig. 2, the experimental results are in satisfactory agreement with the theoretical calculation of Nesis.

Figure 2 presents the results of a statistical analysis of the experimental data on the breakaway diameter. The probability density functions were obtained by the method described by Treshchev [9].

The minimum number of bubbles ensuring 0.99 reliability of the results was calculated from Lyapunov's theorem and the conditions of Neumann and Pearson [10]. This number did not exceed 20, since the variance for the diameters of the bubbles with a given contact angle is very small. As is known [9], curves constructed on the basis of a limited number of measurements approximately reflect the nature of the distribution, but they also give a clear idea of how the experimental data are grouped about vertical straight lines passing through the values of the diameters calculated from Eqs. (1) and (2).

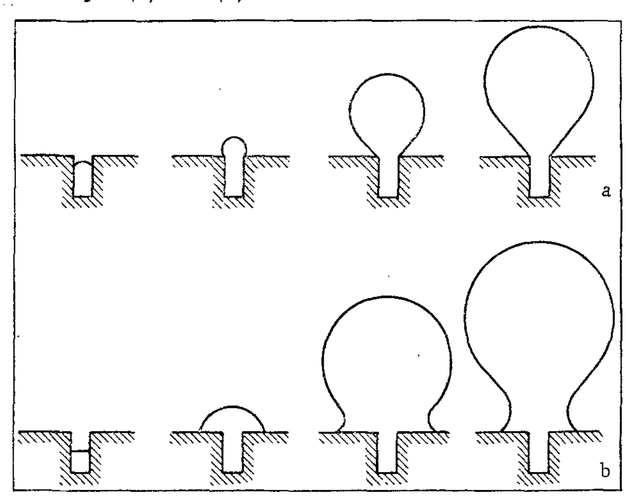

Fig. 3. Bubble growth and separation from wettable (a) and nonwettable (b) pores (schematic).

Along the ordinate axis we plotted values of the probability density of the diameter, i.e., $P(D) = n_i/$

/N, where N is the total number of bubbles with a given contact angle, and n_i the number of bubbles corresponding to the i-th interval $(D, D + \Delta D)$.

Along the axis of abscissas we plotted values of the breakaway diameters. The distribution curves show that Eq. (1) is in good agreement with the experimental data in the region of small contact angles and gives distinctly too high a value of the breakaway diameter for contact angles greater than 100°. The experimental data for these bubbles are grouped about the value given by Eq. (2).

The study of the mechanism of growth and separation of bubbles from pores in the heating surface is of great physical and technical interest.

Our microstudy of the growth of vapor bubbles from cylindrical pores in a horizontal heating surface at different degrees of wettability has produced the following picture of the process.

It is difficult to induce boiling at pores in a clean glass plate. Glass is easily wetted by water, and when the water comes into contact with the glass the pore is filled completely.

At pores $3 \cdot 10^{-4}$ m in diameter we initially observed the separation of 2–3 bubbles (evidently due to the presence of air in the pore before it came in contact with the water), and then the pore ceased to function as an active site. A similar picture was observed upon testing metal pores when the surface was treated with a weak aqueous solution of sodium sulfate.

When a very thin layer of paraffin solution was applied to a glass plate the contact angle increased to about 60° and pores of all the investigated diameters became active centers of vaporization.

The liquid never completely filled the pore, and after separation of a bubble receded somewhat into the pore and was again pushed out by the growing bubble in accordance with the ideas of the author of [11]. When the bubble reached a large size, its base was observed to spread out slightly over the edges of the pore. This pattern of bubble formation and development has been observed on technical metal surfaces, $\Theta = 45°–60°$. Small pores remained active centers of vaporization throughout the observation period; large pores lost their activity after a certain time interval, whose duration depended on the pore diameter. Upon reaching a considerable size the bubble became elongated along the axis of the pore, but its base remained approximately "attached" to the edge of the pore.

In the case of nonwettable pores, $\Theta > 90°$, the following picture was observed (pore $0.2 \cdot 10^{-3}$ m in diameter formed in fluoroplastic, $\Theta = 90°$). First, the liquid is forced out of the pore, the liquid surface inside the pore remaining horizontal. As soon as the walls of the bubble reach the edges of the pore, the phase interface becomes concave, and the base of the bubble leaves the edges of the pore. The contact angle remains almost unchanged. It is interesting to note that before separation the base of the bubble contracts somewhat toward the edges of the pore, and hysteresis of the contact angle is observed. After separation the residue of the bubble considerably exceeds the size of the pore, and the liquid does not penetrate completely into the pore. Subsequent growth proceeds as on a horizontal smooth nonwettable surface.

Figure 3 shows the bubble growth mechanism in schematic form.

NOTATION

θ is the contact angle; D_0 is the breakaway diameter; n_i/N is the probability density of bubble diameters; N is the total number of vapor bubbles with given contact angle; n_i is the number of bubbles in i-th interval $(D, D + \Delta D)$; a is the constant characterizing properties of liquid and its vapor; σ is the surface tension; ρ' and ρ'' are the densities of liquid and its vapor, respectively; g is the acceleration of gravity. All the linear quantities are given in units of the international system.

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Comparison of Experimental Results with the Theoretical Ideas of Fritz and Nesis

Surface	Contact angle $\Theta°$	Breakaway diameter $D_0 \cdot 10^{-3}$, m		
		Nesis	Fritz	Experimental
Copper coated with a solution of potassium butylxanthate	108	6.53	5.4	5.61
	105	6,27	5.4	5.2
	110	6.50	5.4	5.66
Nickel, coated with a solution of paraffin in CCl_4	110	6.54	5.4	5.3
	110	6.54	5.4	6.0
	108	6.53	5.4	5.5
	108	6.53	5.4	5.3
	107	6.53	5.4	5.1
	108	6.53	5.4	5.3
	108	6.53	5.4	5.25
Stainless steel coated with a solution of paraffin in CCl_4	105	6.27	5.4	5.35
	110	6.54	5.4	5.8
	105	6.27	5.4	5.25
	102	6.25	5.4	5.25
	102	6.25	5.4	5.3
	103	6.26	5.4	5.25
	105	6.27	5.4	5.3
	106	6.27	5.4	5.25
	105	6.27	5.4	5.3
	102	6.25	5.4	5.25

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