DEPENDENCE OF THE STABILITY CRITERION OF NUCLEATE BOILING ON THE COMPRESSIBILITY OF THE VAPOR

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The article gives the results of a study of the motion of bubbles and their deformation near the heating surface at different pressures. It was observed that, during the time of their growth, the gaseous medium in the bubbles is in a compressed state.

Nomenclature

R) radius of bubble;
R_h) maximul radius of a deformed bubble in the horizontal plane;
R_v) maximal radius of a deformed bubble in the vertical plane;
γ) specific weight;
B) universal gas constant;
σ) surface-tension coefficient;
p) pressure;
θ) edge wetting angle;
g) acceleration due to gravity;
V) volume;
μ) molecular weight;
C_T) isothermal velocity of sound.

Double primes denote quantities relating to the gaseous medium; single primes denote quantities relating to the liquid medium.

The hydrodynamics of processes of boiling and of the bubbling of a liquid by a gas blown through a porous plate are in many ways analogous. The fact that these processes belong to the same class of physically similar phenomena has been remarked on several articles, both theoretical and experimental [1-4]. In particular, it has been established that the value of the criterion k, characterizing the limiting conditions for the existence of stable nucleate conditions with the bubbling of different liquids, is almost constant when exactly the same gas is blown into the liquids. At the same time, it has been noted that the values of this criterion, with the bubbling of one liquid or another by different gases, depends considerably on the kind of gas blown. Thus, with the blowing of hydrogen, helium, nitrogen, or argon into distilled water, the value of the criterion, k, is equal, respectively, to 0.05, 0.08, 0.16, and 0.20. This fact suggests that the variations of k are determined not only by the physical properties of the boiling liquid, but also by some of the properties of the vapor, which were not taken into account in [1] in the derivation of a formula for determining k.

It was established in [4] that the error introduced into the determination of the value of k results from failure to take account of the distortion of the form of the bubble. If it is assumed that the degree of the breakdown of the sphericity of a bubble is proportional to the change of the pressure in it, then, from the relationship determining the pressure of the vapor in the bubble, which is connected with a change in the curvature of the phase interface, we can obtain a criterion of the form

$$\mathrm{P} = \frac{p_0 - p''}{p_0} = \left(1 + \frac{R_1}{R_2}\right)\frac{\gamma''}{\theta p_0}\left(\frac{\sigma}{\gamma' - \gamma''}\right)^{1/2} \qquad (1)$$

The dependence $k = f(P)$ correlates with complete satisfaction the experimental data on both bubbling and boiling [4].

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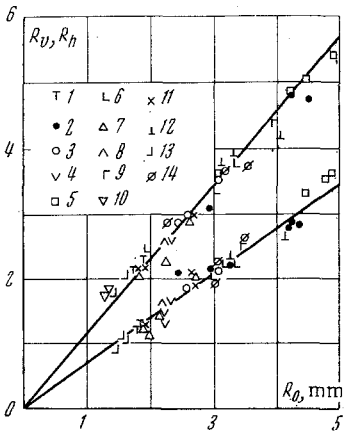

Fig. 1

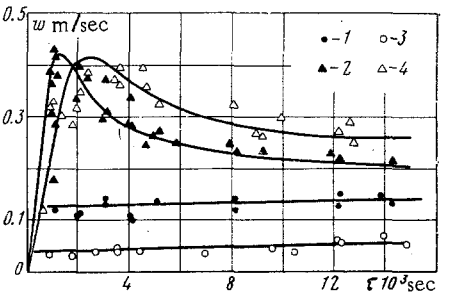

Fig. 2

Fig. 1. Maximal deformation of bubbles at breakaway: points 1, 2, 3, 4) helium, respectively, at p = 9.8, 78.5, 157, and 400 × 10^4 N/m^2; point 5) hydrogen at p = 9.8 × 10^4 N/m^2; points 6, 7, 8) nitrogen, respectively, at p = 9.8, 157, 400 × 10^4 N/m^2; points 9, 10, 11) argon, respectively, at 9.8, 108, 157 × 10^4 N/m^2; points 12, 13, 14 correspond to the vapors of acetone, benzene, and water, in the liquids themselves at p = 9.8 × 10^4 N/m^2.

Fig. 2. Change in the velocity of the front (points 1, 3) and rear (2, 4) points of a bubble at the start of its free motion: 1, 2) helium in water; 3, 4) nitrogen in water.

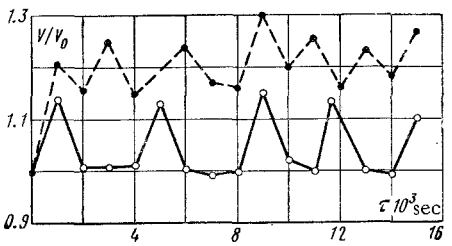

Fig. 3. Change in the volume of the bubbles with time at p = 9.8 × 10^4 N/m^2.

It is obvious that the effect of the properties of the light phase on the value of k manifests within limits bounded by the size of the region near the wall.

As a result of the different compressibilities of the gases used, it is very probable that, even when the size of the bubbles is the same, the pressure in them will be different; this fact can have an effect on the deformation of the bubbles during their generation. In view of this, a study was undertaken of the motion of the bubbles at the heating surface and, in particular, of the breakdown of their sphericity.

The experiments were made in a unit which permitted obtaining individual bubbles, whose growth and motion were recorded using a high-speed moving-picture camera (~ 1000 frames/sec). Argon, helium, and hydrogen, which were introduced into the liquid through replaceable nozzles, were used to generate the bubbles. The sizes of the openings (0.42, 0.92, 1.42 mm) were selected by a calculation aimed at producing bubbles with breakaway diameters close to the capillary constant, and whose rate of emergence does not depend on their size. The unit permitted carrying out experiments not only with gases, but with the vapor of the liquid itself.

A special vaporizer was used for this purpose. The tests were made at pressures from 9.8 × 10^4 to 400 × 10^4 N/m^2. The films obtained were analyzed using a UIM-21 measuring microscope.

By analysis of the moving-picture material, the following quantities were determined: the change in the horizontal R_h^* and vertical R_v^* dimensions; the rate of motion of the rear and front regions of a bubble. The measurements showed that the horizontal and vertical dimensions of a bubble, independently of the kind of gas blown, vary almost linearly with time, in opposite directions. In addition, it was disclosed that, independently of the nature of the gas in the bubbles and their size, the final deformation (a maximal value of the horizontal dimension and a minimal value of the vertical dimension) is such that the following condition is always satisfied (Fig. 1)

$$R_h/R_v \approx 1.65 \qquad (2)$$

In the examination of the moving-picture frames it was observed that the deformation of the bubbles starts with the rear hemisphere, and proceeds here more intensively than in the front hemisphere. Measurements of the rates of displacement of the front and rear surfaces of a bubble brought out their considerable difference. For nitrogen and helium, Fig. 2 gives curves of the change in the velocities of the rear and front points of a bubble as a function of the elapsed time since its separation from the outlet of the nozzle. As is evident from Fig. 2, the velocity of the front point is practically constant, which is in agreement with the results obtained in [5].

The situation is different with the movement of the rear point of the bubble. During the period of growth, the rear point remains fixed, and starts to move only at the moment of breakaway of the "foot" attaching the bubble to the outlet of the nozzle. With separation of the bubble from the outlet of the nozzle, the rate of motion of its rear point increases from zero to some maximum value. The accelerated motion of the rear point is obviously promoted by the rapid decrease in the "foot" of the bubble which, under the effect of the forces of surface tension, becomes rapidly shorter. The initial motion of the rear point takes place with a large acceleration (250-300 m/sec^2). The whole process of the primary deformation of a bubble takes place rather rapidly ($\sim 10^{-2}$ sec); it may therefore be postulated that the great difference in the rates of movement of the rear and front hemispheres must lead to compression of the gas in the bubble.

To check this assumption, careful frame-by-frame measurements were made of the volumes of bubbles, starting from the moment of their breakaway from the outlet of the nozzle. Using a UIM-24 microscope, which permits making measurements with an accuracy down to 1 μ, the coordinates of the surface contour of the bubble were recorded.

Using the data obtained at a magnification up to 100-200 times, the profile of the bubble was plotted on millimeter paper. The profile was then cut by horizontal lines into a number of flat discs, such that, from the segment of the contour of the bubble in each disc, a practically straight line was obtained. The total volume of the bubble was obtained as the sum of the volumes of the "pancakes" (assumed to be round in the plan of the bubble, which is confirmed by moving-picture photography).

Figure 3 gives the results of measurement of the volumes of bubbles of hydrogen and nitrogen. It can be seen that the volume of the bubble at breakaway actually undergoes periodic compression and rarefaction, i.e., it performs a vibrational motion. It is curious that the volume of a hydrogen bubble after breakaway from the nozzle does not revert to its starting value, but fluctuates around a new volume, increased by approximately 20% compared to the breakaway volume. In contrast to a hydrogen bubble, the volume of a nitrogen bubble undergoes irregular fluctuations; for a great part of the time, its simultaneous volume is equal to the volume of the bubble at breakaway.

It was established by supplementary experiments that the volume of the bubble at breakaway increases with a decrease in the molecular weight μ of the gas blown (other conditions being equal). The growth time of the bubbles up to breakaway dimensions also increases with a decrease in the molecular weight of the gas. However, the increase in the growth time of the bubbles is not proportional to the increase in the volumes of the bubbles at breakaway. Thus, the volume of bubbles of hydrogen is 2.76 times greater than that of bubbles of argon, while their growth time exceeds the growth time of argon bubbles by only 1.7 times. This means that bubbles of hydrogen grow faster in comparison to bubbles of argon; therefore, the gas in them must still be strongly compressed during the growth period (this corresponds to the large compressibility of hydrogen). In view of this, the final attainment of an equilibrium volume (before expansion of the gas) takes place after the completion of the growth and separation of the bubble from the outlet of the nozzle.

During the period of expansion, the potential energy of the compressed gas is transformed into the kinetic energy of the motion of small particles of the surrounding liquid and is combined with the energy given up to the liquid by the reciprocating motion of the bubble as a whole.

Thus, with the deformation of bubbles, accompanied by compression of the gas which they contain, work is performed; the value of this work (other conditions being equal) depends on the elasticity of the given gaseous medium and consequently, there must be some relationship between the value of k and the compressibility of the gaseous media. Such a regularity is shown in Fig. 4, in which the experimental values of k for a number of liquids are given in the form of a dependence on the compressibility of the gases, which is the derivative $(dV/dp)_T$ at exactly the same mean pressure. In semilogarithmic coordinates, this dependence has a linear character.

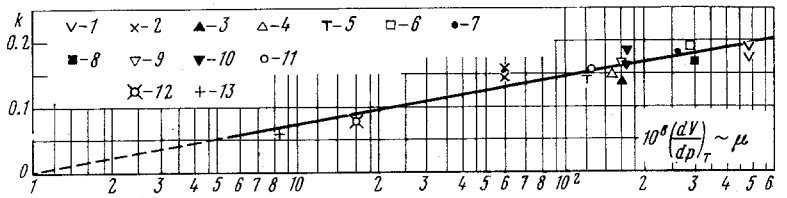

Fig. 4. Dependence of the criterion k on the compressibility of the gaseous medium at $p = 9.8 \times 10^4$ N/m^2 and T = const: point 1) carbon tetrachloride; 2) water; 3) ethanol; 4) methanol; 5) acetone; 6) pentane; 7) benzene; 8) heptane; 9) propane; 10) argon–water; 11) nitrogen–water; 12) helium–water; 13) hydrogen–water.

For correlation of all the experimental data on boiling crises, the coordinate $(dV/dp)_T$ was brought into dimensionless form with respect to the parameter

$$\gamma''\Delta p'' \sim \sigma\left(\frac{1}{R_1}+\frac{1}{R_2}\right)\frac{\gamma''^2}{\gamma'-\gamma''} \qquad (3)$$

The choice of (3) as a pressure scale is due to the fact that the external static pressure p_0 enters as a composite part into the total pressure existing within the bubbles and, therefore, being a constant quantity, does not reflect the changes taking place in the vapor phase with deformation of the bubbles. The part of the total pressure in a bubble which is due to a change in the curvature of the phase interface, differing in value, depends on the properties of the gaseous medium; therefore, it can serve as a measure of the energy expended for compression of the contents of the bubble.

As a result of the reduction of the derivative $(dV/dp)_T$ to dimensionless form we can obtain modifications of the dimensionless parameter P which, instead of the second factor in (1), contain the quantities $\mu/\theta BT$ or $g/\theta c_T^2$. The first of these indicates that the physical property of the gaseous medium which corresponds to the value of the variation of k is the molecular weight. The second variant bears witness to the fact that the dynamic action of the molecular weight of the gas on the liquid interlayers of the two-phase layer near the wall manifests itself in terms of the isothermal rate of propagation of sound in a vapor medium.

LITERATURE CITED

1. S. S. Kutateladze, "The hydrodynamic theory of the change in the boiling conditions of a liquid with free convection," Izv. Akad. Nauk SSSR, Otd. Tekh. Nauk, No. 4 (1951).
2. G. B. Wallis, "Some hydrodynamic aspects of two-phase flow and boiling," in: International Developments in Heat Transfer, Part 2, ASME, New York (1961).
3. S. S. Kutateladze and I. G. Malenkov, "Experimental investigation of the analogy between the processes of boiling and bubbling," Zh. Prikl. Mekhan. i Tekh. Fiz., No. 2 (1966).
4. I. G. Malenkov, "The role of the gaseous medium in the mechanism of the boiling crisis with natural convection," Teplofiz. Vys. Temperatur., 6, No. 2 (1968).
5. R. Cole, "A photographic study of pool boiling in the region of the critical heat flux," A. I. Ch. E. Journal, 6, No. 4 (1960).