ON CHANGES TAKING PLACE IN THE SEPARATION DIAMETER OF A VAPOR BUBBLE WITH INCREASING PRESSURE

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The results of some investigations into the separation diameter of a vapor bubble as a function of pressure during the boiling of water are presented, allowing for changes taking place in the wetting angle and the dimensions of the active center of vapor formation.

Recent investigations [1-4, 6] have shown that in the boiling of a liquid on a heating surface at pressures differing from atmospheric the experimental values of the separation diameters of the vapor bubbles differ from those calculated by the well-known Fritz equation.

Attempts have been made to explain the difference as being due to various kinds of dynamic forces. Thus in [1, 7] allowance was made for the forces of interaction between the bubble and the surrounding liquid, and those between bubbles growing together were considered in [4, 5]. The effect of convection currents in the boiling liquid contributing to an earlier removal of the bubble from the heating surface was

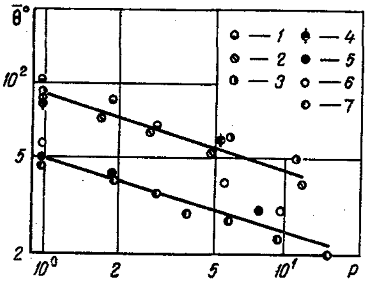

Fig. 1

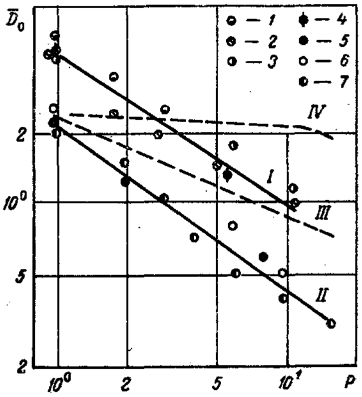

Fig. 2

Fig. 1. Change taking place in the wetting angles $\bar{\theta}°$ with pressure P_s, bar, during the boiling of water on heaters with differing wettabilities [1) copper treated with a solution of potassium butyl xanthate; 2), 3), 4) paraffined steel, permalloy, and nickel; 5) 6), 7) commercial copper, steel, and nickel respectively].

Fig. 2. Separation diameters $\bar{D}_0$, mm, of vapor bubbles as functions of pressure P_s, bar, during the boiling of water on heaters with different wettabilities. I), II) Experimental curves for surfaces with surface-active substances (I) and industrial surfaces (II); III) relationship calculated by the Fritz equation allowing for changes in $\bar{\theta}$ with pressure; IV) change in the capillary constant with pressure (1-7, see Fig. 1).

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considered in [2]. However, this kind of explanation is not entirely acceptable, since the role of inertial forces is the more substantial, the higher the rate of growth of the bubbles and the greater the density of the centers of vaporization. In addition to this, it was shown in [5, 8] that the direction of the dynamic interaction of the bubbles with the liquid and with each other also depended on the growth rate.

In the high-pressure region, in which the growth rate of the bubbles is small and the inertial forces cannot play any major part, an appreciable influence on the separation diameter should also be exerted by such factors as the edge (wetting) angle and the size of the active centers. In studying the dependence of the separation diameter on pressure no allowance was made for the change in wetting angle which occurs with increasing pressure in [6, 7]. It was also considered [7] that active centers of exactly the same size were operative at all the different pressures.

In this paper we shall attempt an experimental estimation of the effect of changes taking place in the wetting angle and the minimum size of an active center with rising pressure on the separation diameter of a vapor bubble.

The experiments were carried out at pressures between atmospheric and 15 bar. In order to achieve boiling with isolated bubbles, moderate heat fluxes were applied to the surface. The minimum thermal loading was 2 W/cm^2 and the maximum 900 W/cm^2. The temperature head varied from 2 to 20°C.

Various degrees of surface wettability were created by treating the heater materials with solutions of surface-active substances using the methods described in [9, 15]. We also tested industrial surfaces not subjected to any special treatment. Boiling was also effected on artificially-created centers – cylindrical pores 0.22, 0.15, 0.12 mm in diameter. The boiling process was recorded by motion-picture photography using a high-speed SKS-1M-16 camera.

Using these photographs, we measured the visible (macroscopic) angle of wetting and the separation diameter of the vapor bubble from magnified images of the bubbles obtained in the Mikrofot instrument. We used the method of analyzing the results described in [9]. The relative error in all these measurements was no greater than 10-12%. From the results of the measurements we plotted the relationships $\overline{\theta}(P_S)$, $\overline{D}_0(P_S)$ calculated by the method of least squares.

The results of the experimental measurements of wetting angles at high pressures are presented in Fig. 1, from which we see that with increasing saturation pressure the wetting angles at boiling diminish. The curves form sections of straight lines; hence the relationship $\overline{\theta}(P_S)$ may conveniently be expressed in the form

$$\overline{\theta} = kP_s^m, \tag{1}$$

where m is the negative power index characterizing the slope of the curves, which in our present experiments equals approximately -0.3. The improvement in surface wettability with rising saturation pressure evidently occurs because of the formation of an oxide film on the surfaces, and also the desorption of surface-active molecules from the heating surface. A comparison between these results and those of [6], in which the experiments were carried out under analogous conditions, shows that in our own experiments there was a sharper dependence of $\overline{\theta}$ on P_S in the particular pressure range studied. Figure 2 shows D_0 as a function of P_S for heaters with various wettabilities during the boiling of water (lines I and II). These curves indicate that the separation diameters vary with pressure in the same way for all the surfaces studied.

In order to compare the experimental values of the diameters with the values of $\overline{D}_0$ determined by the Fritz equation, we calculated the separation diameters from this equation with due allowance for the pressure dependence of the wetting angle and capillary constant. The results are shown in Fig. 2, line III. Line IV shows the change in the capillary constant with rising saturation pressure. We see from these data that, on allowing for the pressure dependence of the wetting angle, the values of the separation diameters $\overline{D}_0$ calculated by the Fritz equation tend to approach the experimental data.

These measurements show that, in the pressure range studied, both in our own experiments and in those of others, the law relating $\overline{D}_0$ to saturation pressure under boiling conditions is a power law:

$$\overline{D}_0 \sim P_s^n. \tag{2}$$

The power index n in our experiments equals -0.7 for all the heaters while the Fritz equation gives -0.38 Our results as to the value of n characterizing the rate of diminution of $\overline{D}_0$ with pressure agree closely with those of [10, 11].

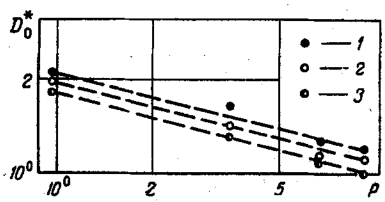

Fig. 3. Dependence of D_0^*, mm, on P_s, bar, for fixed artificial centers: 1) $d_* = 0.22$; 2) 0.15; 3) 0.12 mm.

Thus allowance for the $\theta(P_s)$ relationship reduces the difference between the experiment $\bar{D}_0$ data at high pressures and those calculated from the Fritz equation, but does not eliminate this difference completely. The reason for this lies in the fact that the wetting angle is not the only factor determining $\bar{D}_0$. At high pressures the effect of the minimum dimensions of the active boiling centers on the separation diameters becomes greater.

It is well known that with increasing pressure the number of active centers rises sharply while their minimum size d_* diminishes.

According to [12] a necessary condition for the activity of a pore is that it should contain a certain amount of gas. For saturated boiling at high pressures, at which the liquid is heated to the saturation temperature, bubbles grow by virtue of the fact that vapor passes into the gas space of the pore [13]. It follows from the condition of mechanical equilibrium of the bubble [13] that in pores of diameter

$$d_* = \frac{4\sigma}{P_p(T)} \tag{3}$$

the liquid is completely expelled from the interior of the pore, and even for a very slight difference between the temperatures of the surface and the liquid a pore of the diameter specified then becomes active. It follows from the foregoing equation that, with increasing pressure, finer and finer centers of vaporization will be activated.

Using the equation of [14] relating the separation diameter of the bubble D_0^* to the pore diameter

$$D_0^* = \sqrt[3]{\frac{6\sigma d_*}{g\Delta\rho}}, \tag{4}$$

allowing for (3) we obtain

$$D_0^* = \sqrt[3]{\frac{24\sigma^2}{g\Delta\rho P_p(T)}}. \tag{5}$$

We see from (4) and (5) that the dependence of D_0^* on pressure due simply to the reduction in the minimum pore size d_* is given by

$$D_0^* \sim P_s^{-0.3}. \tag{6}$$

However, the change in the separation diameter for one and the same active center is determined by the change in the function of the liquid parameters $\sqrt[3]{\sigma^2/\Delta\rho}$ which influences the wetting of the surface.

The experimental data relating to the boiling of water on artificially prepared vaporization centers are shown in Fig. 3, as the relationship $D_0^*(P_s)$. We see from Fig. 3 that the separation diameters of the vapor bubbles growing from cylindrical pores diminish with increasing pressure. The dependence of D_0^* on d_* remains intact, i.e., a smaller separation diameter corresponds to a smaller pore size. As regards the experimental fall of D_0^* with P_s, this may be judged from the slope of the curves, i.e., from the power index in $D_0^* \sim P_s^n$; it equals 0.3 for all the centers studied. This value of n coincides with that obtained for the wetting angle m, i.e., on one and the same center of vaporization the separation diameter of the bubble falls with increasing pressure at the same rate as the wetting angle.

It follows from the foregoing measurements that the real rate of change of the separation diameters of the vapor bubbles with rising pressure is determined by the combined influence of several factors, by no means the least important of which are the wettability and the size of the active centers.

NOTATION

D_0, $\bar{D}_0$	is the separation diameter of a vapor bubble and mean value of the same;
D_0^*	is the diameter of the bubble separating from a pore;
θ^0	is the wetting angle;
m, n	are the power indices;
k	is the proportionality factor;
P_s	is the saturation pressure;

d_* is the pore diameter;
σ is the surface tension;
$\Delta\rho$ is the difference between the densities of the liquid and the vapor;
$P_p(T)$ is the vapor pressure inside the pore, similar to P_s.

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