INVESTIGATION OF THE CONDENSATION OF SINGLE VAPOR BUBBLES IN A LAYER OF UNDERHEATED LIQUID

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The dynamics of vapor bubble destruction and its relation to the intensity of heat exchange at the vapor–liquid interface are investigated.

Direct contact of the vapor with liquid, supercooled relative to the saturation temperature, takes place in a number of technological processes of different branches of the industry [1-3]. The above-mentioned type of heat exchange acquires special interest in the case of surface boiling of the liquid [4-6] and in new systems of distilling installations [7, 8].

The intensity of heat exchange in conditions of bubbling of a vapor bubble through a layer of underheated liquid can be determined from the rate of the decrease of its dimensions [9]

$$\alpha = -\frac{\rho'' r}{\Delta T}\frac{dR}{d\tau}. \tag{1}$$

An accurate solution of the problem of the rate of movement of the boundary of a condensing bubble in an underheated liquid is associated with considerable difficulties. The problem is considerably complicated in the case of movement of a condensing bubble relative to the liquid. An approximate solution of the problem for a stationary bubble can be obtained by assigning a certain law of distribution of temperatures of the liquid surrounding the bubble. In any case the condition

$$\lambda' \frac{\partial T(0,\ \tau)}{\partial x} = \rho'' r \frac{dR}{d\tau} \tag{2}$$

must be observed on the instantaneous vapor–liquid boundary ($x = 0$).

A more simple temperature distribution in the liquid can be obtained if the curvature of the surface of the demarcation of the phases is neglected, and if it is assumed that the vapor bubble maintains a constant temperature T_s on this surface during condensation. Hence it is assumed that the temperature jump on the phase boundary is negligibly small which is found to be in accordance with experimental results for pure vapors of nonmetallic liquids [10, 11] and this is assumed on the basis of the theory of film condensation. For these conditions the temperature field in the liquid surrounding the bubbles is expressed by an equation [12]

$$T = T_s - \Delta T \operatorname{erf}\left(\frac{x}{2\sqrt{a'\tau}}\right). \tag{3}$$

From (3) it follows that

$$\frac{\partial T(0,\ \tau)}{\partial x} = -\frac{\Delta T}{\sqrt{a'\pi\tau}}. \tag{4}$$

The combined solution of equations (2) and (4) gives

$$dR = -\frac{\lambda' \Delta T}{\rho'' r\sqrt{a'\pi}}\frac{d\tau}{\sqrt{\tau}}. \tag{5}$$

Integrating (5) taking into account $R(0) = R_0$ and changing over to dimensionless magnitudes, we will obtain

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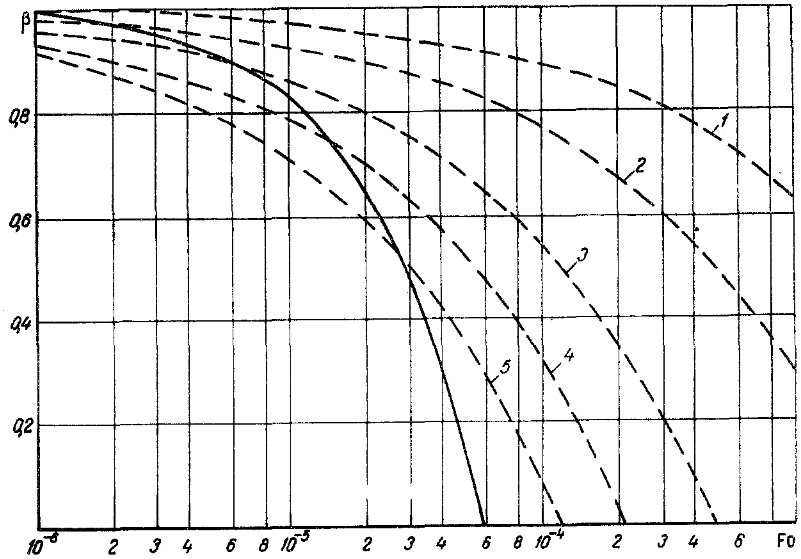

Fig. 1. Destruction of the vapor bubble ($\beta = R/R_0$): 1) Ja = 10; 2) 20; 3) 40; 4) 60; 5) 80; broken curves according to equation (6), continuous curves according to (8).

$$1 - \beta = \frac{2}{\sqrt{\pi}} \mathrm{Ja} \sqrt{\mathrm{Fo}}. \tag{6}$$

Equation (6) corresponds to conditions of symmetrical condensation of a stationary bubble and is a particular solution of a more general problem [13] for a case of destruction of a vapor bubble under the influence of heat exchange, which takes place when

$$B_n = \mathrm{Ja}^2 \frac{a'}{R_0} \sqrt{\frac{\rho'}{\Delta P}} \leqslant 0.05.$$

Experiments [13] carried out in specific conditions of weightlessness (stationary bubble), gave a satisfactory agreement with the solution (6).

The case of condensation of a vapor bubble moving relative to the liquid is of considerably greater practical interest. This phenomenon was investigated by us on an experimental apparatus in which bubbling of the vapor entering through a single aperture into the layer of underheated liquid was achieved. A detailed description of the apparatus is given in [14].

The use of high speed photography (700–2500 frames per second) enabled the formation and dynamic destruction of vapor bubbles to be detected. Analysis of the photographs showed that initially a growth of the bubble takes place directly on the nozzle aperture. As the volume increases the bubble is displaced upwards from the nozzle. Hence a vapor column is formed by means of which the bubble is connected with the aperture of the nozzle. When a certain volume has been reached, then the bubble is torn away from the vapor column and floats upwards. While it moves it decreases in volume and it rapidly disappears completely. The remaining part of the vapor phase on the aperture of the nozzle serves as a nucleus for the new bubble. Treatment of the cinematograms of the process was carried out by means of the photograph decoder ÉDI-452. The recorded configurations of the bubbles, magnified three times, were examined as projections of the cross sections of bodies of rotation. The volume of the bubble was determined by integration using the Simpson formula. The radius of the equidimensional sphere was calculated according to the found value. The time marker of the cine camera enabled the variation R to be traced with respect to time. The first series of experiments was carried out with a nozzle diameter of 3 mm. The experiments showed that the breaking radius of the bubble depends on the underheating of the liquid ΔT. As a result of treatment of the experimental data by a method of least squares the equation

$$R_0 = 29.5 \cdot 10^{-3} \Delta T^{-0.53} \tag{7}$$

was obtained. The range of variations of values R_0 and ΔT in the experiments were: $R_0 = (5.0\text{–}12.5) \cdot 10^3$ m; $\Delta T = 4\text{–}25$°C. The scatter of the experimental points relative to equation (7) is ±10%.

It follows from Eq. (7) that with increase in the underheating of the liquid the breaking radius of the bubble decreases. Similar results were observed in the experiments of [15, 16] on investigating surface boiling.

Measurement of the dimensions of vapor bubbles after they have broken away from the nozzle and when they are floating upwards in the layer of liquid in the case of $B_n \leq 0.05$ was carried out according to the method given above. The result of the series of experiments (Ja = 40–75) is described by the equation

$$1-\beta = c\,\mathrm{Fo} = 1.694\cdot 10^4\,\mathrm{Fo}. \tag{8}$$

Hence the scatter of experimental points in relation to equation (8) was ±30%.

The experimental data are compared with equation (6) in Fig. 1.

As can be seen from Fig. 1, the destruction of the bubbles in the experiments took place more intensively than according to Eq. (6), without taking into account the influence of the forward movement of the bubble in the heat exchange process.

Intensification of destruction of the bubble under the influence of its forward movement is shown theoretically in [17].

According to the data of [17], with increase in the Peclet number the rate of destruction of the bubble increases. Unfortunately, the result obtained in [17] by means of numerical integration of a system of differential equations, corresponds to two values of the Jacob number (Ja = 1, Ja = 10) and for comparatively small values of the Peclet number (Pe = 4500).

In our experiments considerably greater values of the Ja and Pe numbers were observed, which did not make it possible to compare the data of the experiments with the theoretical conclusions [17].

The relationship (8) obtained on the basis of the experiment can be used to evaluate the coefficient of heat exchange in the case of condensation of a vapor bubble according to Eq. (1). It follows from Eqs. (1) and (8)

$$\alpha = 1.694\cdot 10^4 \frac{\lambda'}{\mathrm{Ja}R_0}. \tag{9}$$

The values α, calculated according to Eq. (9), correspond with the results of a number of investigations of drop condensation of water vapor [18].

Equation (9) gives an instantaneous value of α, related to the continuously varying surface of the phase contact.

Together with this the heat exchange coefficient $\bar{\alpha}_0$, averaged over the "life time" τ_t, related to the initial surface of the bubble (where $R = R_0$):

$$\bar{\alpha}_0 = \frac{\alpha}{4\pi R_0^2 \tau_t}\int_0^{\tau_t} 4\pi R^2 d\tau = \frac{\alpha}{\tau_t}\int_0^{\tau_t} \beta^2 d\tau, \tag{10}$$

taking into account Eq. (8) we obtain

$$\bar{\alpha}_0 = \alpha\left(1 - c\,\mathrm{Fo}_t + \frac{c^2}{3}\mathrm{Fo}_t^2\right). \tag{11}$$

By determining the final value of the Fourier number according to the Eq. (8) from the condition $\beta = 0$, we will finally obtain

$$\bar{\alpha}_0 = \frac{1}{3}\alpha = 0.565\cdot 10^4 \frac{\lambda'}{\mathrm{Ja}R_0}. \tag{12}$$

NOTATION

$\mathrm{Ja} = \rho' c' \Delta T/\rho'' r$	is the Jacob number;
$\mathrm{Fo} = a'\tau/R_0^2$	is the Fourier number;
$\mathrm{Pe} = 2uR_0/a'$	is the Peclet number;
ρ', ρ''	are the density of liquid and vapor;
c'	is the specific heat of the liquid;

r	is the heat of vaporization;
R_0, R	are the breaking and flow radius of the bubble;
T_s	is the saturation temperature;
T_f	is the temperature of liquid at a distance from bubble;
$\Delta T = T_s - T_f$;	
τ	is the time;
a'	is the thermal diffusivity of the liquid;
λ'	is the thermal conductivity of the liquid;
u	is the velocity of bubble rise;
$\Delta P = P(T_s) - P(T_f)$;	
$\beta = R/R_0$	is the relative flow radius of the bubble.

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