INFLUENCE OF THE PREOCCLUDED VOLUME OF GAS ON THE SEPARATION DIAMETER OF A BUBBLE

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A mechanism of bubble formation in the escape of gas through a single opening into a liquid layer is proposed. A system of equations is obtained enabling one to determine the separation diameter of a bubble with allowance for the preoccluded volume.

Considerable experimental material has been accumulated on the determination of the separation diameter of a bubble. But even when the diameters of the openings through which the gas escapes into the liquid and the physical properties of the media are the same, the data of different investigations differ considerably from each other [1]. One of the reasons for the disagreement in the experimental data is the influence of the volume of gas in front of the opening through which it escapes (the preoccluded volume), noted experimentally in [2-4]. A function permitting an estimate of this influence has not yet been established, however.

The separation diameter of a bubble is usually determined by solving the equation of motion of the bubble or of its center of inertia [5-8]. On the basis of an analysis of these papers, the equation of motion of the center of inertia of a bubble can be written in the most general form as

$$\frac{d}{dt}\left[\frac{\pi d_{\text{b}}^3}{6}(\rho''+A\rho')\frac{ds}{dt}\right]=\frac{\pi d_{\text{b}}^3}{6}g(\rho'-\rho'')-\pi\varphi_0 d_0\sigma-\frac{c\pi d_{\text{b}}^2\rho'}{8}\left(\frac{ds}{dt}\right)^2+\rho'' A_0(w_0-w_{\text{bo}})^2, \quad (1)$$

where the inertial force, allowing for the associated mass of liquid on the left side, is balanced by the following forces: buoyancy, surface tension in the base, drag, and the dynamic action of the gas stream on the moving surface of the bubble. To solve (1) we use the continuity equation, as is done in [5]:

$$\frac{d(d_{\text{b}})}{dt}=\frac{2Q}{\pi d_{\text{b}}^2}. \quad (2)$$

If we express the connection between the position s of the center of inertia of the bubble relative to the cut of the opening and the bubble diameter using an empirical coefficient

$$s=bd_{\text{b}}, \quad (3)$$

then the velocity of movement of the bubble boundary, as projected onto a plane perpendicular to the plane of the opening, is

$$w_{\text{bo}}=\left(\frac{1}{2}+b\right)\frac{d(d_{\text{b}})}{dt}. \quad (4)$$

With allowance for (2), (3), and (4), we can represent Eq. (1) in the form

$$\frac{b(\rho''+A\rho')}{3}\left(\frac{Q}{d_{\text{b}}}\right)^2=\frac{\pi d_{\text{b}}^3}{6}(\rho'-\rho'')-\pi\varphi_0 d_0\sigma-\frac{c\rho'}{2\pi}\left(\frac{bQ}{d_{\text{b}}}\right)^2+\rho'' A_0 Q^2\left[\frac{1}{A_0}-\frac{2b+1}{\pi d_{\text{b}}^2}\right]^2. \quad (5)$$

The drag coefficient c for a bubble growing at an opening is not known. Therefore, in the first approximation we take it, as in [7], as equal to the drag coefficient for a bubble rising in an infinite volume. In the region of $1 < \text{Re} < 500$, $c = 18.5\text{Re}^{-0.6}$ [7], and for $\text{Re} > 500$, $1/c = 3/8 + 3\sigma/[2gd_{\text{b}}^2(\rho' - \rho'')]$ [9].

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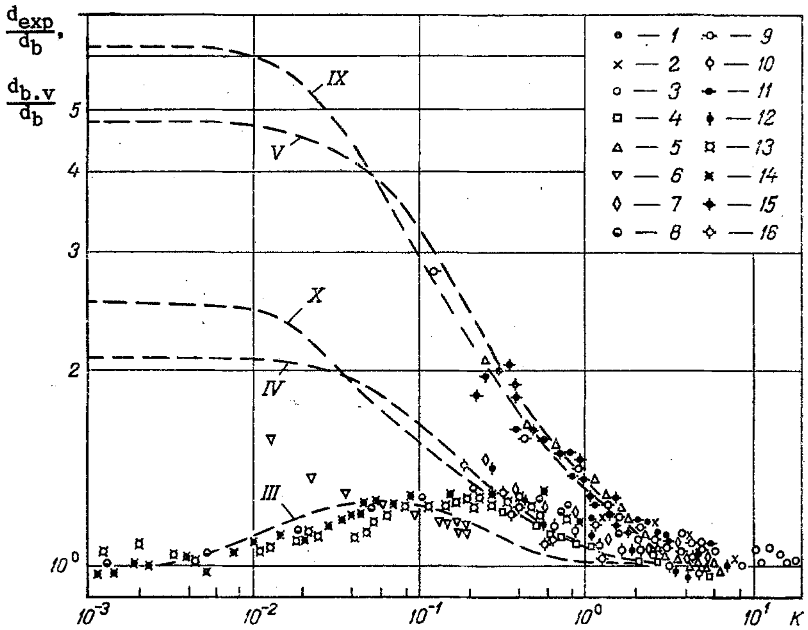

Fig. 1. Relative separation diameter of a bubble as a function of the criterion K: 1) d_0 = 0.0254 m; 2) 0.01905; 3) 0.0127, air–water [6]; 4) d_0 = 0.005 m, V = 0.00035 m^3; 5) 0.005 and 0.004, air–water (author's data); 6) d_0 = 0.01 m; 7) 0.002, nitrogen–water [13]; 8) d_0 = 0.0017 m, air–water [1]; 9) d_0 = 0.005 m, V = 0.004 m^3; 10) 0.005 and 0.00048, helium–water (author's data); 11) d_0 = 0.005 m, V = 0.004 m^3; 12) d_0 = 0.005 m, V = 0.00035 m^3, air–glycerin (author's data); 13) d_0 = 0.002 m; 14) 0.001, nitrogen–water [5]; 15) d_0 = 0.0015 m, P_0 = 0.1 MPa; 16) 0.0015 and 8, nitrogen–water [1]; dashed curves) calculated relative separation diameter of a bubble: IV) d_0 = 0.005 m, V = 0.00035 m^3; V) d_0 = 0.005 m, V = 0.004 m^3, air–water; IX) d_0 = 0.005 m, V = 0.004 m^3, helium–water; III) d_0 = 0.005 m, V = 0.0001 m^3, air–water.

Thus, Eq. (5) enables one to determine the separation diameter of a bubble under the assumption that the gas flow rate Q into the bubble equals the flow rate Q_0 into the preoccluded volume, while the coefficient ϕ_0, allowing for constriction at the base of the bubble, equals 0.66 [10].

In Fig. 1 the experimentally determined values of the separation diameter of a bubble are compared with the corresponding diameters calculated from Eq. (5) with b = 1.7. Here the data of the present investigation are given for different preoccluded volumes. In the investigations of other authors used in the present paper the preoccluded volumes are not indicated. The coefficient A allowing for the associated mass was taken as 11/16 [7]. As is seen from Fig. 1, the results of calculations from Eq. (5) are in satisfactory agreement with the experimental data in the regions of $K < 10^{-2}$ and $K > 3$. In the intermediate region the experimental data differ from the calculated data and, as the results of the present work show, they differ the more, the larger the preoccluded volume. Consequently, in the general case the solution of the equation of motion is insufficient for determining the separation diameter of a bubble.

The research on the influence of the preoccluded volume on the separation diameter of a bubble was carried out at atmospheric pressure on a bubbling column with an inside diameter of 100 mm. Water and glycerin were used as the liquids. The liquid level on the sheet did not exceed 100 mm. The gas was supplied to the chamber through a metal plate 3 mm thick with an opening of d_0 = 5 mm through which it was dispersed into the liquid layer. Air and helium were used in the tests. The preoccluded volume was varied by supplying water to the volume of the chamber in front of the opening. In determining the preoccluded volume, we took into account not only the volume of the gas chamber but also the volume of the

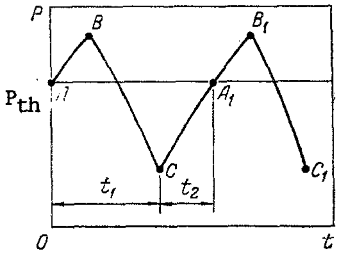

Fig. 2. Diagram of pressure variation in the gas chamber during the formation of a bubble. P, Pa; t, sec.

gas-supply line up to the valve, in which critical discharge took place. The separation diameter of a bubble was calculated from the known gas flow rate and the frequency of bubble separation, which was determined from the frequency of pressure oscillation in the preoccluded volume, recorded with a calibrated induction pressure sensor. One receiver opening of the sensor was inserted into the volume of the gas chamber 20 mm below the plate containing the opening, while the other was connected with the atmosphere. The signal from the sensor was sent to an ID-2I amplifier and then to an N-105 oscillograph. An oscillogram obtained at a low gas flow rate is presented in Fig. 2.

The process of bubble formation was photographed and recorded on movie film, with the oscillograph screen and the opening through which the gas was discharged being combined in the frame. The investigated parameters were varied in the following limits: preoccluded volume 0.00035-0.004 m^3, air flow rate $23 \cdot 10^{-6}$-$588 \cdot 10^{-6}$ m^3/sec, helium flow rate $27 \cdot 10^{-6}$-$1500 \cdot 10^{-6}$ m^3/sec. All the experiments were conducted at atmospheric pressure and $t \approx 20°C$.

On the basis of these experiments we can propose the following mechanism of bubble formation. In the bubbling regime of discharge, the formation of a bubble starts at the moment (point A, Fig. 2) when the pressure in the preoccluded volume reaches the threshold value, defined as $P_{th} \approx P_0 + H\rho' g + 4\sigma/d_0$. During the time interval t_1 the gas flow rate into the bubble, due to the pressures in it and in the preoccluded volume, exceeds the flow rate into the latter. Because of this, the pressure in the preoccluded volume falls below the threshold value and reaches a minimum at the time of separation of the bubble (point C). Then during the time t_2 the gas pressure in front of the opening increases due to the constant flow of gas into the preoccluded volume without the formation of a bubble. At this time the liquid collapses under the action of the developing pressure drop. As soon as the pressure reaches the threshold value (point A_1), the formation of a new bubble starts. With an increase in the flow rate of the gas supplied to the preoccluded volume, the points B and C move upward along the pressure axis, the frequency of bubble separation increases, and the time t_2 decreases. With a decrease in the preoccluded volume at a constant gas flow rate, the amplitude of the pressure oscillation and the frequency increase, and hence the separation diameter of the bubble decreases.

In the jet regime of discharge, the bubbles are formed through the breakup of the gas jet, caused by the instability of the phase interface. In this case the gas flow rate into a bubble during the time t_1 of its formation equals the flow rate into the preoccluded volume. The pressure at the time of bubble separation does not fall below the threshold pressure ($t_2 = 0$), and hence the liquid does not collapse through the opening after the separation of a bubble, and the bubbles are formed continuously. The frequency of bubble separation is practically stabilized and does not depend on the preoccluded volume, i.e., the separation diameter of a bubble does not depend on the latter.

In connection with the fact that the transition from the bubble regime of discharge to the jet regime is connected with loss of stability of the phase interface, it can be determined by a criterial function for the determination of the conditions of stability of flow regimes of a two-phase stream in a vertical pipe [11], and this was responsible for the choice of the criterion K as the scale in Fig. 1. As shown by an analysis of the results of investigations of the separation diameter of a bubble (Fig. 1) and data on the collapse of liquid through the opening [12], this regime is determined by the value $K \approx 3.2$. It should be noted that the same value of the criterion K determines the process of overturning of the film in the annular regime of flow of a gas–liquid mixture in a vertical pipe [11].

In tests with small preoccluded volumes, the frequency of bubble separation reaches a stabilized level corresponding to jet discharge at considerably lower gas flow rates, the values of which depend on the preoccluded volume. In this case the gas pressure in the preoccluded volume falls below the threshold value, indicating that the bubble regime of

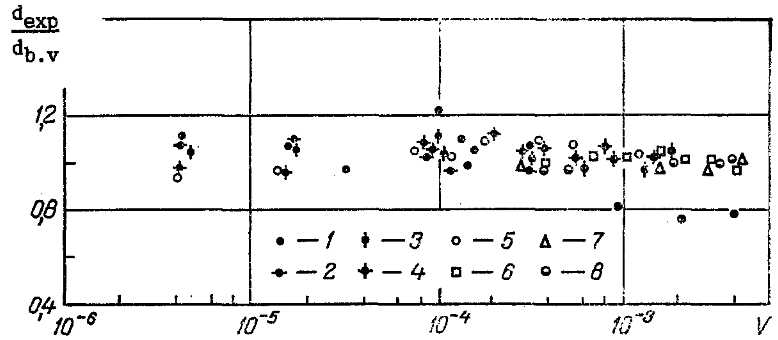

Fig. 3. Comparison of calculated and experimental data on the separation diameter of a bubble: 1) K = 0.0055; 2) 0.072; 3) 0.174; 4) 0.311; 5) 0.488, d_0 = 0.0032 m, air–water [4]; 6) K = 0.78; 7) 1.6; 8) 2.4, d_0 = 0.005, air–glycerin (author's data). $d_{exp}/d_{b.v}$, dimensionless; V, m^3.

discharge is still retained. Thus, stabilization of the frequency is a necessary but not a sufficient condition for a transition from the bubble to the jet regime of discharge.

According to the adopted model, the gas flow rate into a bubble is determined by the pressures in the bubble and in the preoccluded volume. Taking the pressure in the bubble as equal to the pressure at its center, for a bubble growing at the opening we write

$$P=(H-s)\rho' g+\frac{4\sigma}{d_b}+P_0. \quad (6)$$

The pressure in the preoccluded volume can be expressed as

$$P_c=\bar{P}+\Delta P, \quad (7)$$

where we represent the average pressure $\bar{P}$ in the form

$$\bar{P}=P_b+\frac{Q_0^2\rho''}{2A_0^2}. \quad (8)$$

We determine the pressure change ΔP due to the change in the mass of gas in the preoccluded volume by using the equation of state for an ideal gas in an isothermal process,

$$\Delta P=\frac{gRT}{V}\Delta M. \quad (9)$$

The change ΔM in the mass of gas in the preoccluded volume in the time t_1 is

$$\Delta M=Q_0\rho'' t_1-\frac{\pi d_b^3}{6}\rho''. \quad (10)$$

We write the time of formation of a bubble as

$$t_1=\frac{\pi d_b^3}{6\bar{Q}}. \quad (11)$$

Assuming that the functions determining the gas flow rate through the opening are valid for any time t_1, with allowance for losses we write the expression for the volumetric flow rate of gas into the bubble at the time immediately preceding separation:

$$Q=\mu A_0\sqrt{\frac{2k}{k-1}RT\left[1-\left(\frac{P}{P_c}\right)^{\frac{k-1}{k}}\right]}. \quad (12)$$

If we limit the velocity ds/dt of movement of the bubble at the time of separation to the velocity w_∞ of rise of the bubble in an infinite volume, which can be determined in accordance with the adopted drag coefficients, then from Eq. (12) with allowance for (2), (3), (6), and (7) we can determine the average flow rate $\bar{Q}$ of gas into the bubble:

$$\bar{Q}=\frac{Q_0}{1+\frac{6V}{\pi g\rho'' RTd_b}\left\{\frac{P_0-g\rho' bd_b+\frac{4\sigma}{d_b}}{\left[1-\frac{\pi^2 d^2 w_\infty^2(k-1)}{8gkRTb^2\mu^2A_0^2}\right]^{\frac{k}{k-1}}}-P_{th}-\frac{Q_0^2\rho''}{2A_0^2}\right\}}. \quad (13)$$

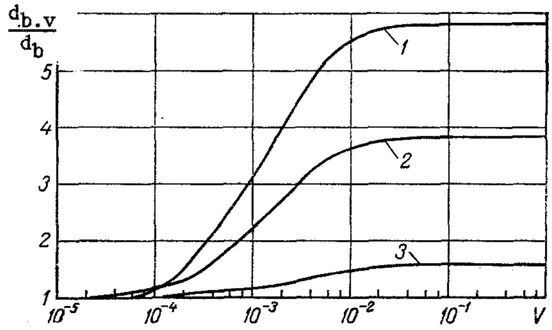

Fig. 4. Influence of the volume of the gas chamber on the separation diameter of a bubble for an air–water medium, d_0 = 0.005 m: 1) K = 0.001; 2) 0.1; 3) 1.0.

Assuming that the flow rate of gas into the bubble is constant and equal to the average rate determined from Eq. (13), we rewrite (1) with allowance for (2), (3), and (4) in the form

$$\frac{b(\rho'' + A\rho')}{3}\left(\frac{\bar{Q}}{d_b}\right)^2 = \frac{\pi d_b^3}{6}(\rho' - \rho'')g - \pi\varphi_0 d_0\sigma - \frac{c\rho'}{2\pi}\left(\frac{b\bar{Q}}{d_b}\right)^2 + \rho'' A_0 \bar{Q}^2\left[\frac{1}{A_0} - \frac{2(b+1)}{\pi d_b^2}\right]^2. \quad (14)$$

Thus, the joint solution of the algebraic equations (13) and (14) enables us to determine the separation diameter of a bubble with allowance for the preoccluded volume of gas.

In Fig. 1 the dashed lines show the variation of the ratio of the separation diameter $d_{b.v}$ of a bubble determined from the solution of Eqs. (13) and (14) to the bubble diameter d_b determined from Eq. (5) for μ = 0.5. Curves IV, V, IX, and X were calculated for the same conditions under which the experimental results with the corresponding Arabic number designations were obtained. The calculated curve III corresponds to the character of the distribution of the test points obtained in [1, 5] and treated in the coordinate system chosen by the author. In accordance with this, it can be assumed that the experimental data in [1, 5] were obtained with small preoccluded volumes.

In Fig. 3 the experimental data obtained in [4] and by the author with variation of the preoccluded volume and constant gas flow rates (K = const) are compared with the calculated separation diameter of a bubble determined from (13) and (14). As follows from Figs. 1 and 3, the functions proposed above enable one to calculate the separation diameter of a bubble satisfactorily with allowance for the preoccluded volume and to estimate its influence.

The character of the influence of the preoccluded volume on the separation diameter of the bubble is shown in Fig. 4 on the example of the function constructed for an air–water medium and d_0 = 5 mm. It follows from Fig. 4 that the influence of the preoccluded volume can be divided into three regions. In the first ($V < 10^{-4}$ m^3), the separation diameter of a bubble hardly depends on the preoccluded volume and can be determined from Eq. (5). In the second region (10^{-2} m^3 > V > 10^{-4} m^3) an increase in the preoccluded volume in the bubble regime of flow leads to an increase in the separation diameter of a bubble, which can be determined by a joint solution of Eqs. (13) and (14). In the third region ($V > 10^{-2}$ m^3), a further increase in the preoccluded volume does not lead to an increase in the separation diameter of a bubble.

Thus, the influence of the preoccluded volume on the separation diameter of a bubble is limited not only by jet discharge, the transition to which occurs for K ≈ 3.2, but also by the size of the preoccluded volume itself.

NOTATION

$K = w_0''\sqrt{\rho_0''}/\sqrt[4]{g\sigma(\rho' - \rho'')}$, criterion of stability of the regimes of flow of gas–liquid systems; $w_0'' = Q_0/A_0$, reduced velocity of the light phase; ρ'' and ρ', densities of the light and heavy phases, respectively; σ, surface tension coefficient; A_0, area of the opening; $Re = d_b \cdot w_{bo}/\nu'$, Reynolds number; d_b, bubble diameter; w_{bo}, velocity of movement of the bubble boundary; ν', coefficient of kinematic viscosity; d_{exp}, separation diameter of a bubble determined experimentally; H, level of liquid on the sheet; P_0, pressure above the liquid surface; R, gas constant; T, temperature; k, adiabatic index.

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INFLUENCE OF ADVERSE ACCELERATIONS ON THE OPERATION OF AN "ANTIGRAVITY" HEAT PIPE

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The authors present results of an experimental investigation of the influence of accelerations directed along the heat-transfer vector on the operation of heat pipes with separate channels for vapor and liquid.

There is a considerable gulf between the capability of elements of electronic equipment (EE) and heat pipes (HP) to function under the action of vibrations, accelerations, and other factors unfavorable for heat pipes. The literature has practically no information on the operation of heat pipes under the action of dynamic, arbitrarily directed accelerations of more than 1g.

The case of heat transfer in the direction of the vector of the accelerations acting on the heat pipe is more complex for the operation of a heat pipe, since it requires added expenditure of energy to move the liquid heat transfer agent into the heat supply zone against the action of mass forces.

The hydrostatic pressure can be compensated for by increasing the capillary potential due to a reduction of the size of pores of the heat pipe wick, which in turn leads to a

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